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Functional tolerancing of surface texture – a review of existing methods

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Abstract

Surface texture parameters can provide a link between texture, its processing and function. Recent surveys and industrial experience have shown that the ISO 25178 areal surface texture parameters have not received the level of traction in industry that was predicted when introduced despite the fact that the areal parameters were predicted to have more functionally relevant characterisations than the ISO 4287 profile parameters. The objective of the paper is to enable more functionally relevant specifications of surface texture to be taken up by industry and the scientific community by increasing the knowledge of the ISO 25178 texture and novel feature parameters, and their potential use, as well as knowledge about methods for establishing functionally relevant surface texture specifications. In the paper, existing methods for functional tolerancing of surface texture are reviewed and discussed, examples of applications are given and a direction for continued research is presented.

Keywords: Functional Tolerancing; Surface texture;

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1. Introduction

Surface texture parameters facilitate control of surfaces by assigning the surface a quantitative value, calculated via a series of mathematical operations. Several specification standards and parameters for surface texture have been used over the years. For example, the most commonly used parameter is the profile height parameter *Ra*, the arithmetic mean height of the texture [1,2]. In 2012, a new standard was published where areal surface texture parameters were introduced, ISO 25178-2 [3], in addition to the profile texture parameters of the commonly used standard ISO 4287 [1].

However, recent surveys and industrial experience have shown that the ISO 25178 areal surface texture field parameters have not received the level of traction in industry that was predicted [2,3]. This is despite the fact that the areal parameters were predicted to have more functionally relevant characterisations than profile parameters [4].

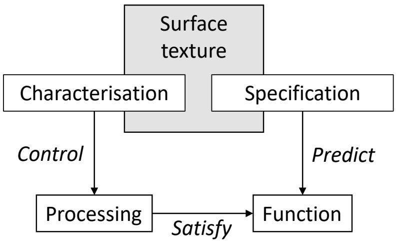

Fig. 1. The link between surface texture, its processing and function, adapted from [5].

The purpose of characterising or specifying a surface using texture parameters is to create a parametric description that can be used to control the processing or to predict the performance of the surface. Thus, parameters can provide a link between surface texture, its processing and function, see Fig. 1. However, to be useful, the parameters used in the parametric description must be relevant for the process or function [5–7].

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The profile parameters can be useful as a simple approach for controlling manufacturing processes rather than specifying surfaces for functional performance. With them, a manufacturing process that produces surfaces that function satisfactorily can be monitored by monitoring the surface texture. Changes to the process will show as changes in the surface texture. However, profile parameters seldom provide a direct link between surface texture and functional performance [4,8], and if they do, it is usually within very tight spatial frequency bandwidths. Exceptions would be cases where both the manufacturing process and the function of the surface are unidirectional and parallel.

More functionally relevant specifications can be accomplished by carefully selecting an appropriate combination of filtering and parameters for characterisation, or by using advanced feature-based approaches [9–11]. Examples are given later in the paper. Separating texture from form and selecting appropriate filters are challenging and have been studied extensively, examples are given elsewhere [10,12].

Even though the first paragraph in the paper states that the surface texture field parameters are not being used as extensively as could have been expected, there is a change in this direction. As methods for manufacturing and inspection are becoming more sophisticated, so are the demands regarding surface functionality; engineered and structured surfaces are being utilised more [4,13,14]. At the same time, more advanced filters have been developed as well as the new ISO 25178-2 standard for surface texture parameters [4,15].

The work presented here is part of a collaboration between researchers from surface metrology and engineering design communities. The objective of the collaboration is to enable more functionally relevant specifications of surface texture to be taken up by industry and the scientific community. This objective will be accomplished by increasing the knowledge in the design community of the ISO 25178 texture and novel feature parameters, and their potential use, as well as knowledge about methods for establishing functionally relevant surface texture specifications. The increased use of more functionally significant surface texture specifications in design engineering will increase the use in other fields, for example, in manufacturing.

In the paper, existing methods for functional tolerancing of surface texture are reviewed and examples of applications are given in section 2, advantages and drawbacks of the methods are discussed in section 3 and a direction for continued research is presented in section 4.

2. Functional tolerancing of surface texture

Tolerancing is carried out at the design phase of the product realization loop but has consequences in the pre-production and production phases, as well regarding inspection preparation and inspection respectively, see Fig. 2 [16,17].

To be able to carry out any kind of functionally relevant tolerancing of surface texture, some relation between function and surface texture needs to be established. The relationship could be realised as a physics-based mathematical model suitable for simulations, experimentally proven functional correlations or some other kind of model.

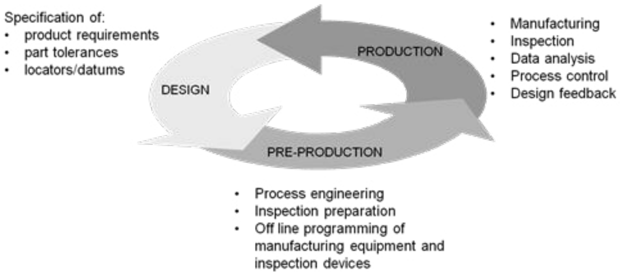


Fig. 2. Product realization loop as presented in [17], adapted from [16].

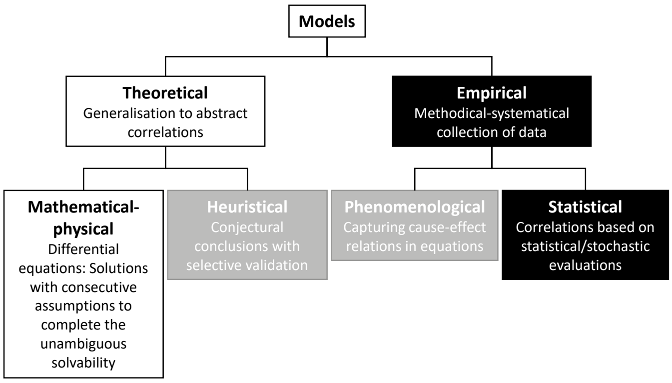


Fig. 3. Systematic of models based on their physical interpretation, adapted from [18].

Models can be characterised as white, grey or black based on their physical interpretation, see Fig. 3 [18]. Theoretical models are based on valid physical interrelationships and the group contains ‘white box models’, that are purely mathematical-physical, and theoretical models that are extended by heuristical elements and are so called ‘grey box models’. Empirical models are based on statistical correlations. ‘Black box models’ are based on statistical correlations solely. Empirical models can also be grey box models when phenomenological by using physically-based correlations [18].

Several methods have been developed for performing functional tolerancing of surface texture and methods use models of some kind.

2.1 A model and simulation-based approach

A detailed methodology for tolerancing surface texture through a function-oriented process chain has previously been developed [19–21]. The approach was developed with special emphasis on the ability to deal with structured surfaces with small features where properties other than purely geometrical ones are also functionally relevant. The methodology is based on physical modelling and enables optimisation, see Fig. 4. Descriptions of the surface texture are not made through texture parameters, such as those found in e.g. ISO 25178-2, but rather through dimensional descriptions, such as widths, heights, etc.

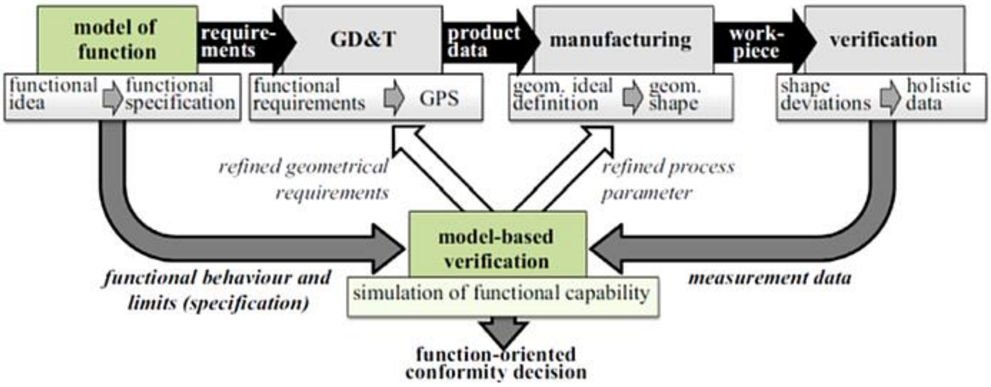


Fig. 4. Approach for a function-oriented process chain [20].

To model the function in a relevant way it is critical to have an adequate physically based model of the surface function. In references [19–21], examples are given on applications of the methodology, including the texture of a printing roll used for transferring ink, crankshaft texture for friction reduction and sealing of an injection valve.

Of the given examples, only the printing roll has a model of the function detailed enough to perform optimisation of the texture, see Fig. 5 (a) where the geometrical model is presented and (b) where simulation results are presented. The following labels are used in the geometrical model: bridge width BW, engraving depth ED, engraving width EW and flank angle γ.

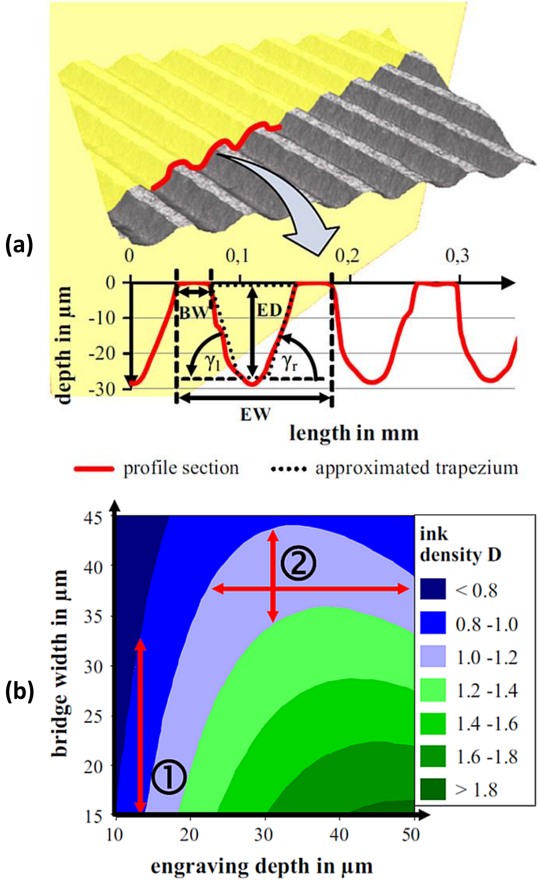


Fig. 5. (a) Areal measured anilox roll microstructure and extracted profile section (with engraving depth ED, bridge width BW, engraving width EW and flank angle γ). (b) Contour plot for ink density as a function of bridge width and engraving depth [20].

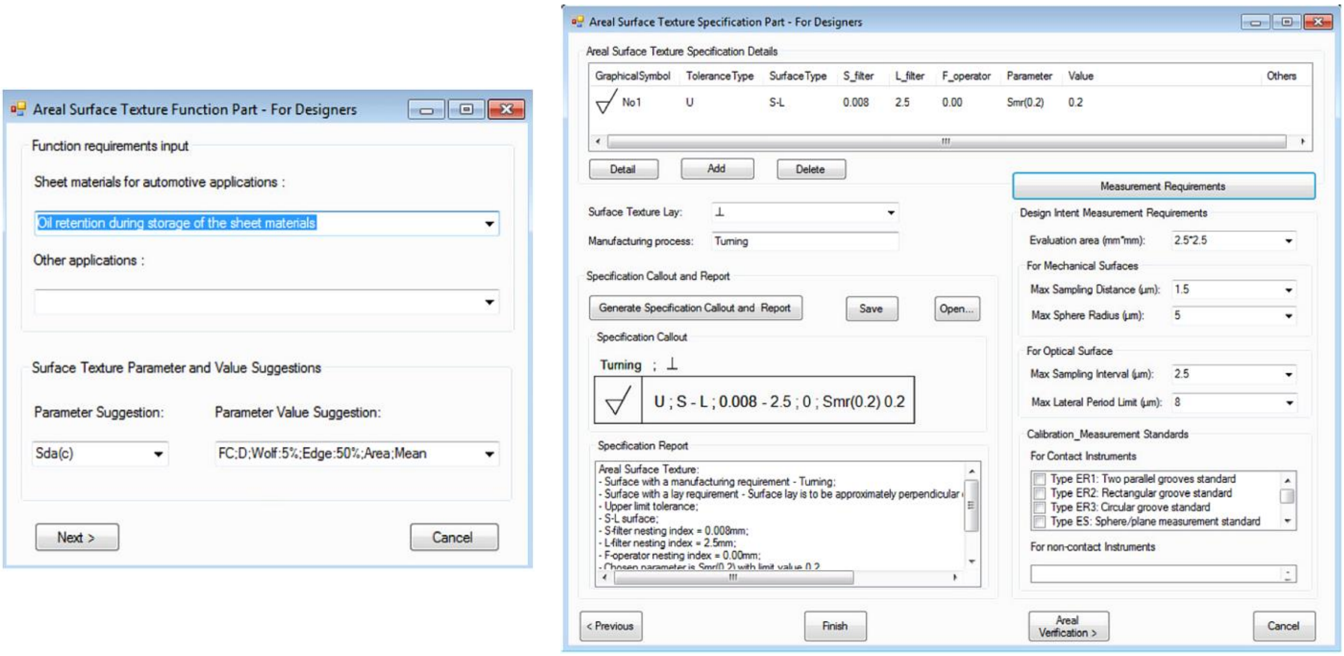
Simulation of the function is made using a physics-based mathematical model. The required functional ink density was 1.0D ±0.08D, where the ink density value D is given in a logarithmic scale. D can have values between 0.001D (minimal ink density = bright) and 2.0D (maximal ink density = dark). Ink density variations in the range of ±0.08D are not visible to the human eye. The simulation result, see Fig. 5 (b), is showing the combined effect on ink density of varying bridge with and engraving depth. In area 1, a broad tolerance for the bridge width is possible (from 15 µm to 32 µm). However, the tolerancing range for the engraving depth must not exceed 5 µm to ensure an ink density variation is below 0.16D. Area 2 is more stable regarding ink density fluctuations. In area 2, a tolerancing range for engraving depth from 20 µm to 50 µm and from 34 µm to 44 µm for bridge width can be allowed [21]. The simulation result gives two possible tolerance ranges for satisfying the functional requirement and the ranges of area 2 would likely provide a more easily controlled process because of the wider tolerances.

2.2 Axiomatic design

An approach for specifying surface texture based on functional requirements using axiomatic design has been presented elsewhere [22]. Using this methodology, first defined customer needs (CNs) [23] are used to develop functional requirements (FRs) and constraints (Cs) [24]. Design parameters (DPs) are selected to meet the FRs and comply with the Cs. Process variables (PVs) are selected to manufacture the DPs. Surface texture parameters, or other descriptions of the surface geometry, can be used as design parameters. Care must be taken to ensure that the functional requirements are independent and that they do not contain physical information, as this would reduce the solution space [24]. The independence of functional requirements be accomplished by formulating the customer needs on a higher abstract level rather than something related to a solution [22]. The functional requirements, related to the customer needs, are what need to be satisfied within some tolerance [23,24].

Examples of applications that the axiomatic design approach is discussed for are rotating lip seals, road pavement and tire interface, and sport shoes and playing surface interface [22].

Several DPs can be integrated if functional independence can be maintained. Considering the surface as the object, then some aspects of the topography can be integrated physically.



Areal Surface Texture Function Part - For Designers

Function requirements input

Sheet materials for automotive applications : Oil retention during storage of the sheet materials

Other applications :

Surface Texture Parameter and Value Suggestions

Parameter Suggestion: Sda(c)

Parameter Value Suggestion: FC;D;Wolf:5%;Edge:50%;Area;Mean

Areal Surface Texture Specification Part - For Designers

Areal Surface Texture Specification Details

GraphicalSymbol	ToleranceType	SurfaceType	S_filter	L_filter	F_operator	Parameter	Value	Others
No1	U	S-L	0.008	2.5	0.00	Smr(0.2)	0.2	

Surface Texture Lay: ⊥

Manufacturing process: Turning

Specification Callout and Report

Specification Callout

Turning ; ⊥

U ; S - L ; 0.008 - 2.5 ; 0 ; Smr(0.2) 0.2

Specification Report

Areal Surface Texture:
- Surface with a manufacturing requirement - Turning;
- Surface with a lay requirement - Surface lay is to be approximately perpendicular
- Upper limit tolerance;
- S-L surface;
- S-filter nesting index = 0.008mm;
- L-filter nesting index = 2.5mm;
- F-operator nesting index = 0.00mm;
- Chosen parameter is Smr(0.2) with limit value 0.2

Design Intent Measurement Requirements

Evaluation area (mm*mm): 2.5*2.5

For Mechanical Surfaces

Max Sampling Distance (µm): 1.5

Max Sphere Radius (µm): 5

For Optical Surface

Max Sampling Interval (µm): 2.5

Max Lateral Period Limit (µm): 8

Calibration_Measurement Standards

For Contact Instruments

☐ Type ER1: Two parallel grooves standard
☐ Type ER2: Rectangular groove standard
☐ Type ER3: Circular groove standard
☐ Type ES: Sphere/plane measurement standard

For non-contact Instruments

(a) (b)

Fig. 6. Examples of the graphical user interface of CatSurf showing the Function (a) and Specification (b) components [31].

Care must be taken to separate the aspects to maintain functional independence which requires methods for characterisation and specification with enough sophistication, generally more than is supplied by commonly used height parameters such as the average roughness for profiles or surfaces (*Ra* or *Sa*). The relative vertical position on the surface is one way of achieving independence for some kinds of functions, particularly those involving fluids. For example, on pavements, the deepest valleys can help to remove water from the tire interface, reducing hydrodynamic lubrication by the water. The texture on the highest regions would supply the topographic features for controlling friction with the tire. Functional independence can also be achieved through separation by scale. For pavement, the surface is smooth at the scale of the wheel-road interaction for a comfortable ride and rough on the scale of the compound and tread patterns in the tire for adequate friction in wet and dry conditions [22].

2.3 Expert systems

Several attempts toward creating expert systems to help designers to specify surface texture have been reported. The interactive surface modelling (ISM) system, which also incorporated the ability to simulate topographies, was developed and implemented on a personal computer as a prototype in the 1990's with an interface to a commercial CAD software [25,26]. It could be used for specifying topography, using standardised surface texture parameters, and for evaluating changes to the topography using virtual manufacturing. The objective was to develop a system where the user could retrieve appropriate information about the surface specification and functions with the aim to guarantee that preparation and production receive the optimal control parameters for each function related surface specification.

The foundation for an internet based surface texture information system was developed in the early 2000s [27]. The objective was to enable a database of topography datasets and functional requirements to be aggregated that could be used as an expert system. It would collect and store large datasets over a sufficient time to enable a cause and effect analysis between surface finish and function on the one hand and surface finish and manufacturing process on the other. The system included most of the, at that time, standardised and advanced analysis tools and a database for surface texture.

A statistical approach for determining appropriate parameters for specifying and characterising surfaces have been developed [28–30]. The method uses the bootstrap method and MesRug expert system [29]. For a number of given datasets, the system can test combinations of texture parameters and filters and give suggestions on how the surfaces should be specified. The datasets can be either from simulations or from measurements.

In 2014, details were published on an integrated surface texture information system for design, manufacture and measurement, CatSurf [31]. It is a comprehensive system, with interface into commercial CAD software. The purpose is that a user of the system does not have to be an expert in surface texture standards but can still, based on functional needs, get a recommended specification of surface texture and verification protocol. Compared to earlier systems it uses a more advanced database, based on category theory, to be able to better support complex data structures and to reflect the complicated relationships among engineered artefacts and surface texture GPS standards. The system has a graphical user interface for defining required function, selecting manufacturing process, creating specifications and creating protocols for verification, see Fig. 6. It also offers integration in several commercial CAD software such as AutoCAD and SolidWorks [31].

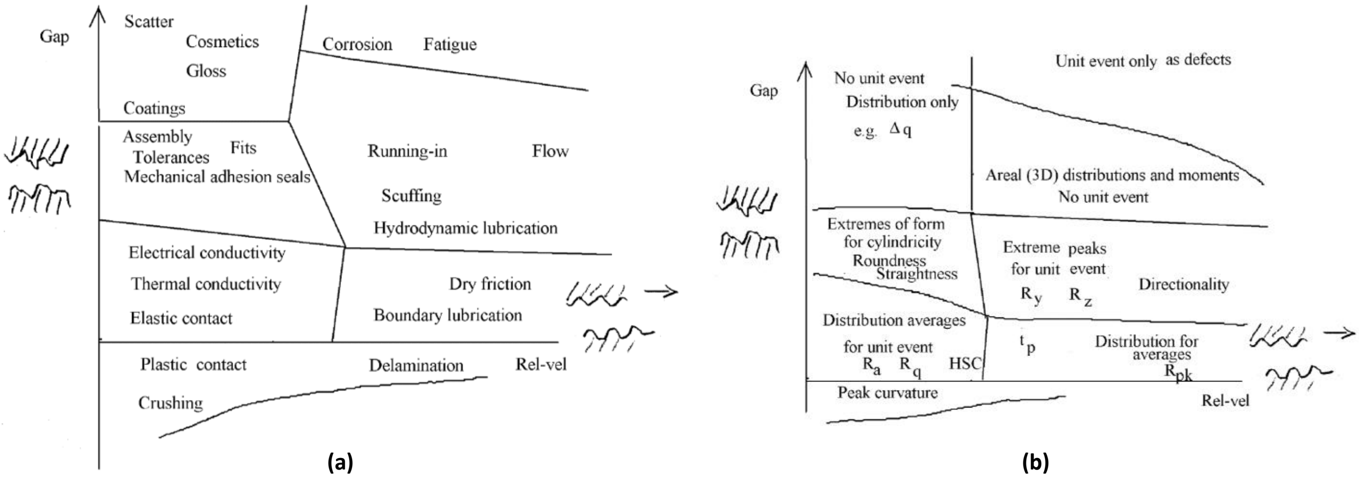


Fig. 7. (a) Function map, (b) Surface parameter map. Adapted from [8].

Common for all systems mentioned above is that they rely on correlations between functionality and surface specifications which make them only as good as the data that has been fed into the databases. They do not use any mathematical-physical modelling of the function.

2.4 Relating function to surface texture

Another approach for categorising surface functions with the objective of helping designers to select appropriate texture parameters to base specifications on is function maps [8]. Functions are classified in a two-dimensional space, or coordinate system, with surface separation on the y axis and relative motion on the x axis, see Fig. 7 (a) [8]. This classification seems to be able to incorporate many of the common surface functions in engineering applications such as static contact for load bearing, elastic contacts, electrical and thermal conductivity, running-in, flow and even optical effects as light scatter. The approach has been further developed regarding contact mechanics and tribology, using the plasticity index [32].

Related to the function map, also a surface parameter map has been presented, see Fig. 7 (b), where texture parameters are suggested for specification of surfaces for certain functions [8].

In the literature, examples of functions and related surface specifications can be found. For instance, many such relations are provided in a review by Thomas [32]. For example, the relation between the two roughness parameters *Spk* (reduced peak height) and *Svk* (reduced valley depth) and polishing defects on mould steel and the effect of changing height roughness parameters and on engine oil consumption.

3. Discussion

Comparing the approaches described above, there are some fundamental differences. First, the model and simulation-based approach does not use surface texture parameters for specification of the surface geometry. Instead it uses discrete dimensional specifications, such as widths and heights for the geometrical features that constitute the texture which provides unambiguous surface descriptions that enable the use of mathematical-physics-based, with ‘white box models’, simulation allowing optimisation to be performed. Also, surface textures that are complicated to specify using the standard parameters, e.g. highly structured surfaces, can be simulated. A drawback is that the output is also in this form when standardised texture parameters might be expected to be put on drawings and used in verification.

However, it could hypothetically be possible to use a combination of uncorrelated standard texture parameters to specify also textures that have been optimised with physics-based simulations by characterising them virtually, providing an adequately unambiguous texture specification [33,34].

Most of the other approaches described in this review use ‘black box model’ statistical correlations for relating texture to function that does not allow optimisation in the same way. In most cases the relation between surfaces characterised using some texture parameter and a functional performance can be known from experiments. Synergetic effects, relating changes to combinations of texture parameters, on functional performance is not commonly known.

An expert system, integrated with CAD tools, such as the CatSurf system, is certainly an attractive possibility. Such a system could be useful, especially if large amounts of experimental results, relating texture and function, are incorporated. It does not allow for optimisation though, as discussed above.

A combination of the different approaches could possibly provide the functionality needed to simulate surfaces and optimise surface functionality and at the same time provide unambiguous surface texture specifications using the standardised ISO 25178 areal texture parameters. However, attention needs to be given to the uncertainty arising from the difference between the actual specification operator and the functional operator that defines the function of the surface [35,36].

4. Conclusions

Over the years, much work has been done to facilitate functional tolerancing of surface texture. Several expert systems have been developed for specifying surface texture and methodologies for simulation-based optimisation of surface texture.

A way forward could be to combine some of the developed approaches to create a system enabling the functionality needed to simulate surfaces and optimising surface functionality and at the same time providing unambiguous surface texture specifications using the standardised ISO 25178 areal texture parameters.

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