Spatial frequency decomposition with bandpass filters for multiscale analyses and functional correlations

Spatial frequency decomposition with bandpass filters for multiscale analyses and functional correlations

IOP Publishing Surf. Topogr.: Metrol. Prop. 12 (2024) 035031 https://doi.org/10.1088/2051-672X/ad6f2f

Surface Topography: Metrology and Properties

RECEIVED
8 January 2024

REVISED
13 July 2024

ACCEPTED FOR PUBLICATION
14 August 2024

PUBLISHED
29 August 2024

PAPER

Spatial frequency decomposition with bandpass filters for multiscale analyses and functional correlations

Christopher A Brown[1], François Blateyron[2], Johan Berglund[3,4], Adam J Murrison[1] and Jack Jacob Jeswiet[5]

[1] Surface Metrology Laboratory, Mechanical & Materials Engineering Department, Worcester Polytechnic Institute, Worcester, MA, United States of America
[2] Digital Surf, 16 rue Lavoisier, 25000, Besançon, France
[3] Department of Manufacturing Processes, RISE Research Institutes of Sweden, Mölndal, Sweden
[4] Department of Industrial and Materials Science, Chalmers University of Technology, Gothenburg, Sweden
[5] Mechanical Engineering, Queen's University, Kingston ON, Canada

E-mail: brown@wpi.edu

Keywords: roughness, surfaces, filtering, multiscale characterization

Abstract

To address the essential problem in surface metrology of establishing functional correlations spatial, frequencies in topographic measurements are progressively decomposed into a large number of narrow bands. Bandpass filters and commercially available software are used. These bands can be analyzed with conventional surface texture parameters, like average roughness, Sa, or other parameters, for detailed, multiscale topographic characterizations. Earlier kinds of multiscale characterization, like relative area, required specialized software performing multiple triangular tiling exercises. Multiscale regression analyses can test strengths of functional correlations over a range of scales. Here, friction coefficients are regressed against standard surface texture parameters over the range of scales available in a measurement. Correlation strengths trend with the scales of the bandpass filters. Using bandpass frequency, i.e., wavelength or scale, decompositions, the R^2 at 25 μm, exceeds 0.9 for Sa compared with an R^2 of only 0.2 using the broader band of conventional roughness filtering. These improved, scale-specific functional correlations can facilitate scientific understandings and specifications of topographies in product and process design and in designs of quality assurance systems.

1. Introduction

Functional correlations in surface metrology refer to dependencies that can be established experimentally between parameters characterizing the topography of a surface and characterizations of its behavior, as well as between characterizations of processes that create or modify surface topographies and parameters characterizing those topographies (ASME B46.1 2019).

A key element to solving the essential problem in surface metrology of elucidating strong functional correlations between surface topographies and their behavior is explained in this paper. The richness and value of selecting appropriate scales for meaningful academic or industrial inquiries with practical relevance through multiscale regression are established. This paper shows how to use bandpass filters effectively with commercially available software for spatial frequency decompositions to generate such multiscale characterizations as are required for multiscale regressions.

The method is demonstrated using standard roughness parameters (ISO 25178-2:2021) and multi-scale regression analyses to elucidate strong functional correlations in narrow scale bands (ASME B46.1 2019). The standard parameters selected here, height, hybrid and volume are not usually used in multiscale characterizations and analyses (Brown *et al* 2018). Relative-length and relative-area are also standard parameters (ASME B46.1, ISO 25178-2), althought they are inherently multiscale characterizations and do not lend themselves to bandpass filtering as used here.

There is extensive literature on different kinds of filters for spatial frequency decompositions, e.g., Brown *et al* 2018, ISO 16610, and modal filters in

LeGoic *et al* 2011 and Shao *et al* 2023. It is beyond the scope of this paper to review this extensive literature. Only one, commonly used kind of filter is used here for frequency decompositions. A distinctive feature here is the test of strengths of functional correlations as a demonstration of viability of this method for creating value for evidence-based design tolerancing and scientific insights.

Much of the previous work on multiscale geometric characterization was done with specialized software that is not readily available. For example, Berglund *et al* in two papers (2010a & 2010b) found strong functional correlations between die topography and friction with metal sheets using area-scale analysis and bandpass filtering. Both methods required specialized software (Brown *et al* 1993, Agunwamba 2010). Area-scale analysis was patented by Brown *et al* (1994, U.S. 5,307,292). Similar bandpass filtering can be found in VDA 2007. The current efforts show how multiscale characterization can be done using commercially available software, and standard filtering and height parameters.

Two ways that surface metrology can provide value and intellectual richness, are: one, by confidently discriminating surfaces by their topographies, and, two, by discovering strong functional correlations. The latter are relations between topographies and their processing or performance (Savio *et al* 2016, ASME B46.1 2019, Brown 2021). Functional correlations are valuable for manufacturing processes and product design, and they provide evidence for geometric dimensioning and tolerancing. The intellectual richness provided by functional correlations can provide insights into fundamental topographic interaction phenomena. Establishing functional correlations has been challenging for machined components (M'Saoubi *et al* 2015) and crucial for function (Denkena *et al* 2011, Deltombe *et al* 2015). Most authors do not provide results of regression analyses that are required for evaluating the strength of correlations.

The lack of regression analyses could be said to impoverish much of the published academic work that has passed peer-review. This impoverishment from avoiding regression analyses for establishing strengths of correlations might go unnoticed because regression analyses are missing so often. Nonetheless including results of regression analyses could be a requirement for academic papers on surface metrology dealing with functionalities. Indeed the academic richness of evaluating the strength of correlations as a potential requirement for future work could go overlooked because so few papers have yet gone to this length.

The experimental establishment of functional correlations, both for performance and processing, generally appears to depend on certain factors. Some studies have placed an emphasis on the importance of the resolution of optical measurements for finding functional correlations, and the need to make measurements that can be related to the functional performance of the surface (Leach *et al* 2015a, Leach *et al* 2015b).

Looking specifically at ball end milling, studies have discussed the issue of scale relating to the selection of the measurement region, the cutoff wavelength for filtering, and the lenses used for measuring topographies with a confocal microscope (Denkena *et al* 2015). For machining by broaching, studies have applied multiscale analysis to the study of chatter through frequency analysis of measured profiles, accelerations, and forces. This allowed for an efficient identification of chatter marks associated with a weakened tool (Axinte *et al* 2004). Multiscale characterizations with relative area when used to evaluate simulated machined surfaces showed the importance of combining machining kinematics with microscale features on cutting edges leads in simulations (Lavernhe *et al* 2014).

Geometric characterization of topographies at scales appropriate to the topographic interactions of interest can enable discoveries of functional correlations. Correlation strengths can vary with scale. The strongest correlations have been found in a narrow range of scales—much narrower than is conventionally used for evaluating roughness (Berglund *et al* 2010a, Berglund *et al* 2010b, Vulliez *et al* 2014). Principles for surface metrology to facilitate the discovery of functional correlations have been proposed, consisting of two axioms, scale and characterization, and two corollaries, measurement and statistics (Brown *et al* 2018, Brown 2021).

The relative effectiveness of Gaussian, wavelet, modal decomposition, and bandpass filters for multiscale analyses to test for correlation strength and the ability to discriminate for a variety of topographies has been studied (Goïc *et al* 2016). They found that Gaussian is preferred for periodic and stochastic surfaces. Conventional characterization parameters can be highly correlated with each other, as has been shown with conventional filtering and cross-correlation analyses (Nowicki 1985). Nowicki found that several parameters could be indicative of the same geometric properties.

A geometric multiscale analysis, length-scale relations for the coastline of Britain, was described by Richardson and expanded on by Mandelbrot (1967, 1975) in developing fractal geometry. Guibert *et al* (2020) compared three means of doing multiscale analyses patchwork, box, and motif, which are based on fractal analyses. Length-scale finds relative lengths as a function of scale and was applied to topographic profiles (Brown and Savary 1991). Length-scale was later extended to area-scale analyses of areal topographic measurements to find relative areas as functions of scale (ASME B46.1 ch.10, ISO 25158-2) with specialized software (Brown *et al* 1993). Area-scale analysis is currently available commercially in MountainsMap® (DigitalSurf, Besançon).

The current work establishes functional correlations with friction using multiscale characterization through bandpass filters and surface texture parameters, without specialized software. Friction has an important role in all fields of engineering and is also true for metal forming. For sheet metal forming, the primary example is the production of aluminum foil (less than 0.2 mm thick) where surface roughness and lubrication are paramount. It has previously been established that the surface finish affects both the rolling efficiency and surface quality (Schmitt *et al* 2016). Metal forming is a heavy user of models in production processes; however, model errors include uncertainties related to the use of a process model including surface conditions (Allwood *et al* 2016). In metal forming, the surface topography of the workpiece and tool has significant influence on the friction, lubrication, and final surface quality of the formed component, especially when liquid lubrication is applied (Bay *et al* 2010). Such friction coefficients have been regressed against multiscale areal curvatures to show strong functional correlations (Bartkowiak *et al* 2018), and multiscale analysis and display of their anisotropy has been published (Berglund *et al* 2011).

Size effects have been investigated in determining friction coefficients, which could be relevant to discussion of scales of interaction with topographies. No comprehensive work using direct measurement of friction forces in experiments on size effects exists in the literature (Vollertsen *et al* 2009). Generally, friction coefficients appear to increase with decreasing size of the contact region (De Chiffre *et al* 2000). For dies and molds, the shape and surface topographies of die cavities and friction coefficients govern sliding velocities, temperature, and interface pressures (Shivpuri and Semiatin 1992). Recent work on mechanical surface modification processes, aimed at structuring or smoothing surface topographies, has used arithmetic average roughness (Ra) and the peak to valley roughness (Rt) to study the influence of the state of residual stresses (Schulze *et al* 2016). While these are of interest, the sizes investigated do not approach those of the topographic features and bandpass widths in the present study.

The objective of the present study is to test and demonstrate a novel method to perform multiscale analyses with bandpass filters using commercial software to elucidate functional correlations between surface topographies and friction. Previously, this has been done using specialized software which is no longer available.

This study uses a subset of topographic characterization parameters defined in ISO 25178-2:2021. Multiscale characterizations are accomplished by applying overlapping Gaussian filters, one high-pass and one low-pass, to the measured topographies with a progression of central wavelengths in MountainsMap®. Then separately multiscale regression analyses are done, as previously mentioned in the literature (Berglund *et al* 2010a, Berglund *et al* 2010b, Vulliez *et al* 2014). In addition, correlations between the characterization parameters are calculated, like the work done with conventional S-F filtering and cross-correlation analyses (Nowicki 1985), although they are compared here as functions of scale.

The structure of this paper shows the logical development leading to concise conclusions:

- The preparation of the specimens and performance tests are described first, followed by the topographic measurement method, then the friction coefficients, as determined previously, are given following immediately in section 2 on methods.
- Essential elements are conventional filtering, bandpass filtering (figure 1), and multiscale characterizations. The latter two are key contributions of this paper, and are presented in methods, section 2.1.
- Procedures for multiscale regression analyses and the resulting evaluation of the multiscale functional correlations are described in section 2.2 (figure 2).
- Section 3 presents renderings of topographic maps after several kinds of filtering (figure 3). These images provide visual impressions of measuring and treatment of measured topographic data on one surface preparation. Figure 4 continues with topographic maps to provide visual impressions comparing two other surface preparations.
- Regression analysess of a conventional parameter, average roughness (Sa), show how correlation strengths at three different scales of the bandpass filtering (figure 5). Table 2 compares the strengths of correlations with conventional and bandpass filtering.
- Figure 6 shows further how correlation strengths vary with scale. Then a final figure (7) shows strenths of cross correlations for some conventional characterization parameters as a function of scale.

2. Methods

The strengths of functional correlations are evaluated using linear regressions to determine linear dependence with the correlation coefficient R and coefficient of determination, R^2. The latter is the proportion of the variation in the dependent variable, friction, coefficient that is predictable from the variation in the independent variable, a characterization of the topography. The strength of the correlations depends on how topographies are characterized.

The friction between a sheet strip (DP600, 1 mm thick, Ra = 1 μm) and tool pins was measured by means of a bending under tension test method with 1 g m^{-2} of lubrication. The resulting friction coefficients were then calculated.. This method was described previously in

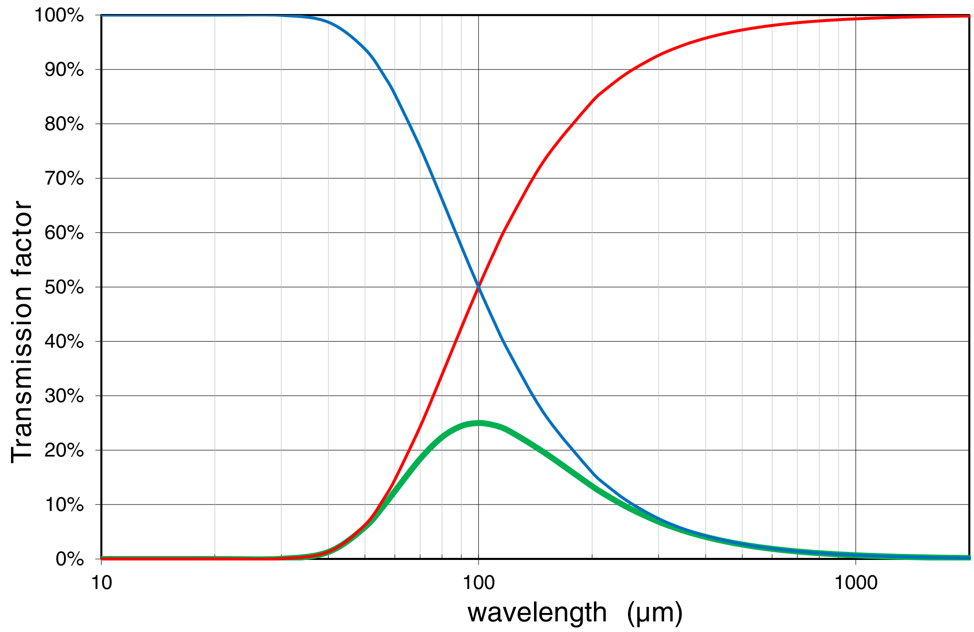

Figure 1. Filter transmission. Wavelengths are transmitted according to the red line (low-pass or S-Filter) and the blue line (height-pass or L-Filter). The green is the 'zero bandwidth' bandpass.

detail by Bay *et al* (2008) and Andreasen *et al* (2006). Details of the specific tests have been described in Berglund *et al* (2010a, 2010b). A sheet strip bends over stationary pins with clamps on the strip each side of the pin. The sheet slides over the test pin under tension. Loads are applied to the strip through the clamps by hydraulic cylinders and measured with strain gauges. Frictional torque on the test pins is measured directly with a piezoelectric torque transducer. Friction coefficients are calculated from the normal loads on the sheet and the tangential loads on the pin.

The pins were prepared with two different levels of finish milling (fine and rough) of a nodular cast iron and two tool steels (table 1).

Three topographic measurements were made on each of the pins with a Wyko RST Plus white light interferometric microscope, at 10× with a measurement region (i.e., 'measurement area' in ISO 25178-600 section 3.1.4) of 577 × 428 μm and a sampling interval of 785 nm. While 800 μm is a typical cutoff for many measurements, this measurement is only is 500 × 500 μm. The 800 μm cutoff is based on tradition rather than on the needs of actual experimental interest. In this case the size of the measurement region extends well above the scale of the area-scale, smooth-rough crossover in Berglund *et al* (2010b figure 3), which is about 10 000 μm^2 or 100 μm. The smooth-rough crossover is the scale above which the surface appears smooth and below which it appears rough (ASME B46.1 ch.10). A larger measurement size would increase the sampling interval and thereby decrease the resolution in the measurement. *A priori*, the scales of interaction, indicated by the scale of strongest correlation in multiscale analyses are not known (Brown 2021). These scales are logically below the smooth-rough crossover scales. Therefore, selecting scales much larger than the smooth-rough crossover would diminish the likelihood of finding the scales of strongest correlations.

Mean friction coefficients are listed in table 1. Standard deviations were below 0.003 (Berglund *et al* 2010a, Berglund *et al* 2010b).

2.1. Filtering and multiscale characterization

Conventional filtering creates S-F surfaces with a median 3 × 3 short wavelength de-noising filter, S, with an effective cutoff below about 2.35 μm, based on the sampling interval, and a second order long wavelength filter, F, effectively over 400 μm ('Cylindrical form' in MountainsMap ver 5). Missing data points, i.e. height values, were filled in before filtering. Similar to that used previously in VDA 2007, the 'zero-bandwidth' bandpass filter used here (Blateyron 2017) was created using two classical Gaussian filters with a single cutoff value, λ_C: first in a high-pass mode and again in a low-pass mode. The transmission factor of this normal Gaussian filter is one half at the cutoff wavelength. When one high-pass and one low-pass filter are combined at the same cutoff wavelength, as is done here, the combined transmission factor is a quarter at the cutoff wavelength (figure 1). It is compensated by a factor of 4, to obtain a full transmission at the cut-off value. The combination of the two filters gives new characteristics for the bandpass filter:

$$\frac{u_2}{u_0} = 4\exp^{-\ln(2)\left(\frac{\lambda_c^2}{\lambda^2}\right)}\left(1 - \exp^{-\ln(2)\left(\frac{\lambda_c^2}{\lambda^2}\right)}\right) \quad (1)$$

Where u_2 is the final signal, u_0 is the initial signal, and λ is the wavelength. Such a filter attenuates wavelengths on both sides of the cutoff as shown in figure 1

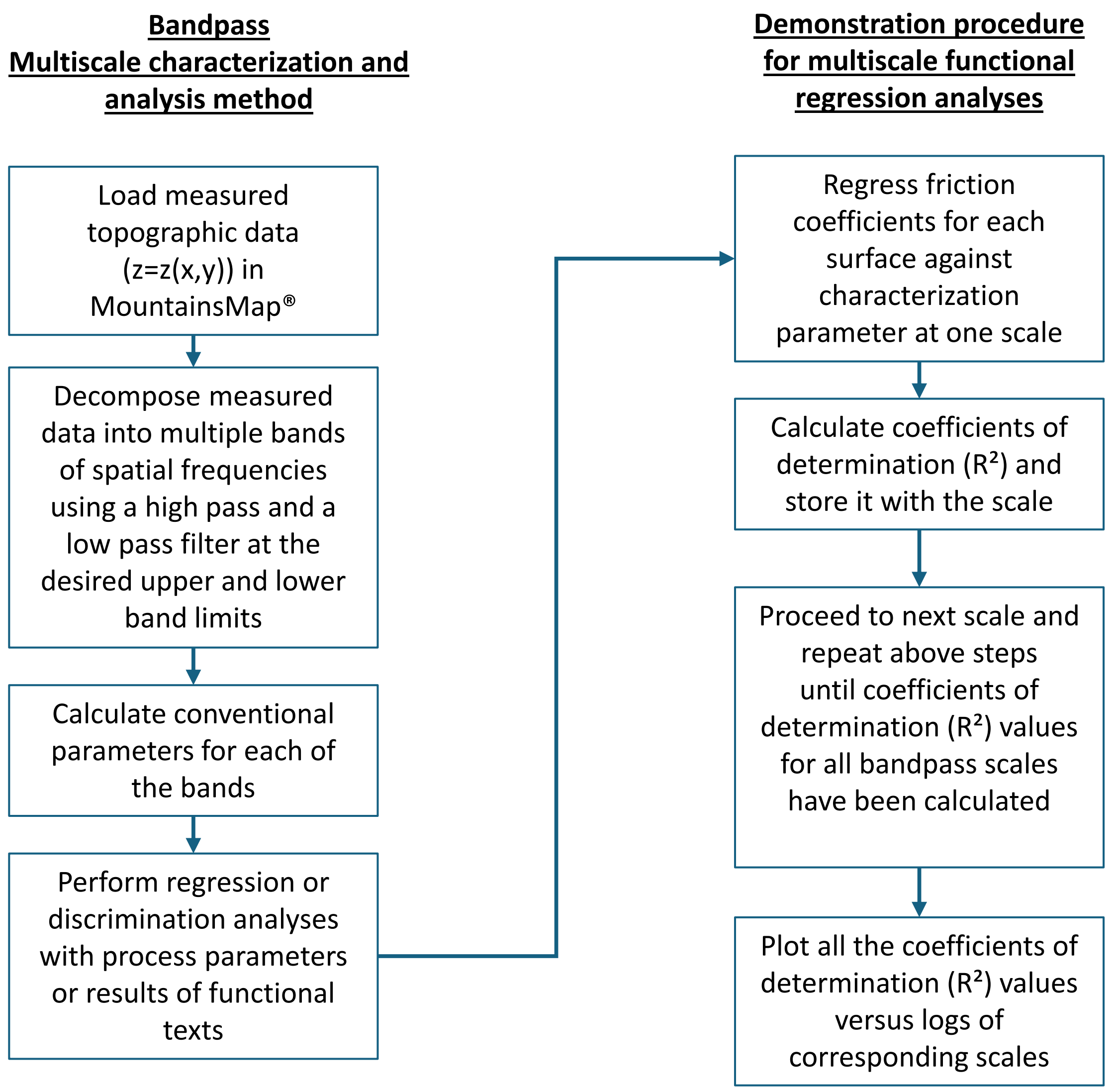

Figure 2. General description of the bandpass multiscale procedure.

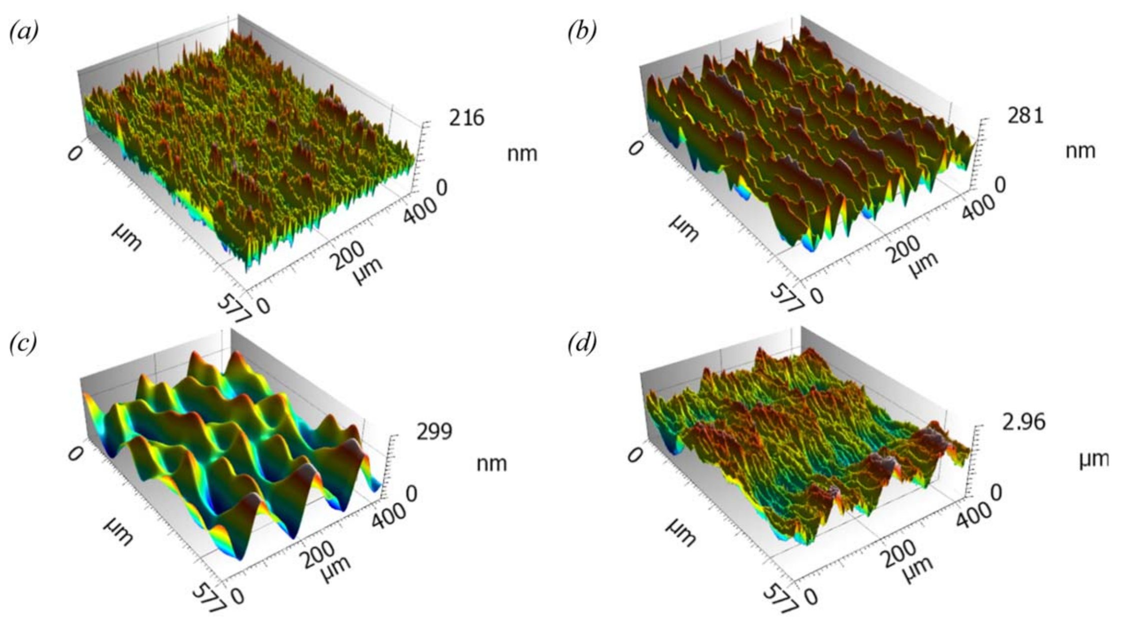

Figure 3. Carmo fine ($\mu = 0.133$) with bandpass filtering at scales 9 μm (a), 25 μm (b), and 100 μm (c), and S-F filtering (d).

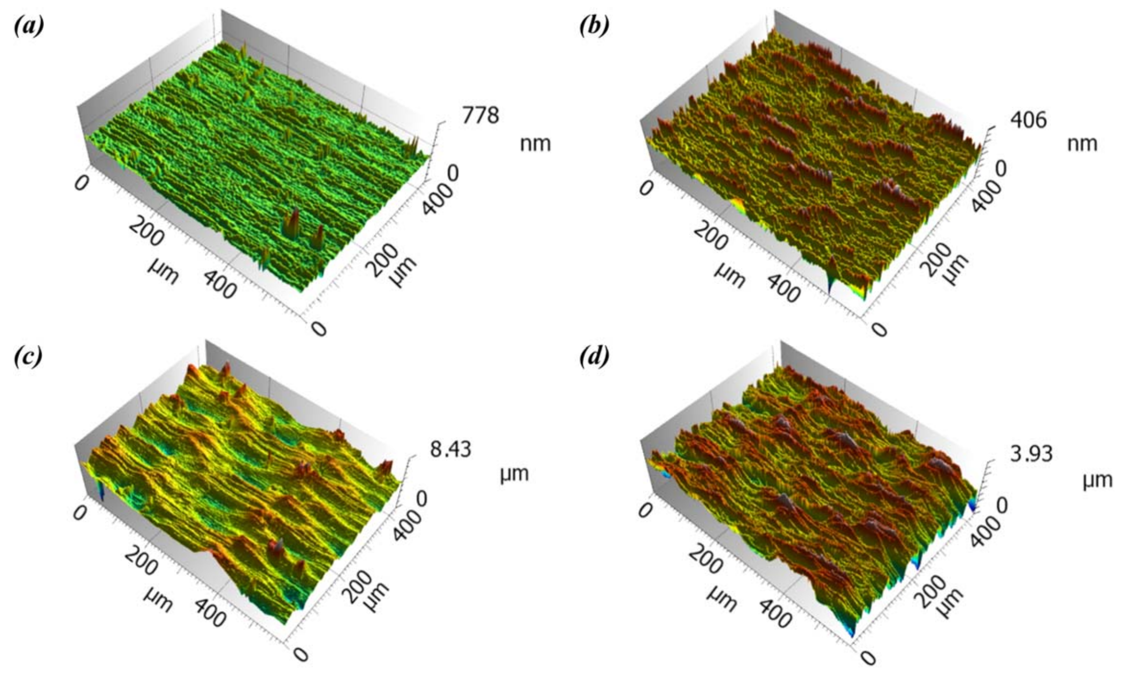

Figure 4. GGG70L Fine ($\mu = 0.140$) left and Sleipner Rough ($\mu = 0.161$) right, bandpass at scale 9 μm above (a) and (b) and S-F below (c) and (d).

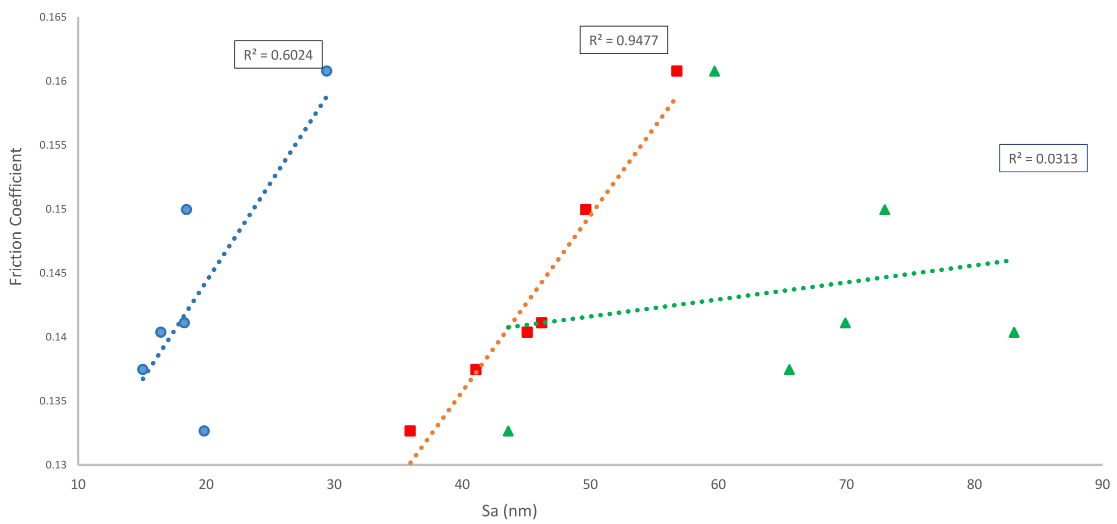

Figure 5. Friction coefficients from table 1 (Berglund *et al* 2010a, Berglund *et al* 2010b) versus Sa for three bandpass filters. Blue is at 9 μm, red at 25 μm, and green 100 μm.

and is defined in ISO 16610-21:2011 for profiles and ISO 16610-61:2015 (ISO 16610-61:2015) for surfaces. The curve is not symmetrical because a true low-pass filter is not used; rather it is complementary to the high-pass filter.

To calculate the actual bandwidth of this so-called 'zero-bandwidth' filter, first calculate where the amplitudes of each are ½ of the maximum. Equation (1) shows this to be $0.6006\lambda_C$ and $2.092\lambda_C$, for the left and right curves respectively. Subtracting these shows that the actual bandwidth of this zero-bandwidth filter is $1.49\lambda_C$, which is clearly not zero, nor is it constant with respect to the central wavelength, λ_C.

In this study, the form was removed, missing points were filled in, and then a filter bank was created using a progression of the square root of two between the central wavelengths. This factor leads to two filtration bands per octave, i.e. when the cut-off is doubled. If three bands were required, a factor of the cubic-root of 2 would have been chosen. Considering the size of the measured region and the sampling interval, there are then twelve filters applied according to equation (1), with central

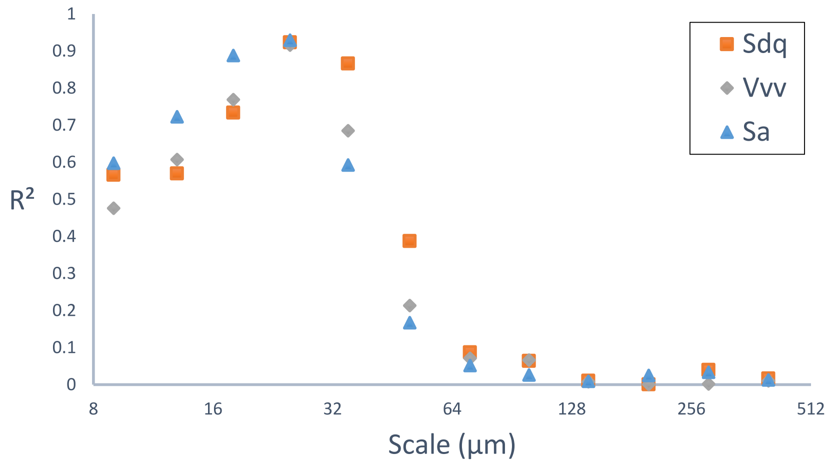

Figure 6. Results of multiscale regression analyses showing coefficients of determination (R^2) of friction with Sdq, Vvv, and Sa versus scale.

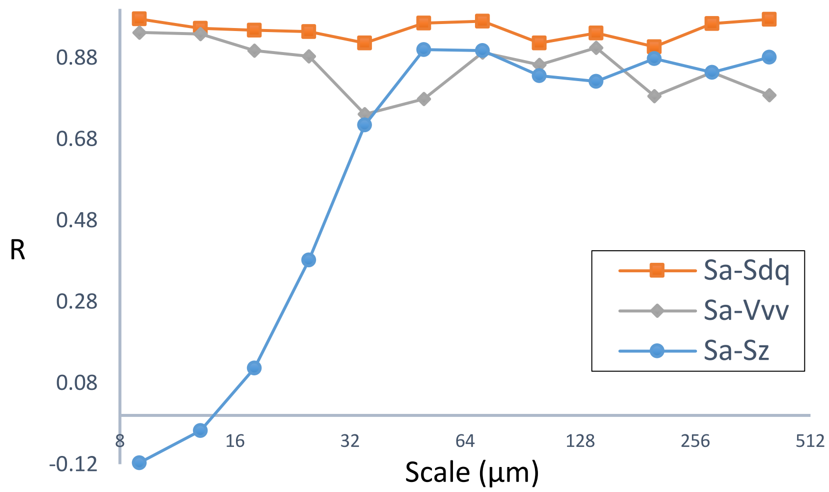

Figure 7. Cross correlation strength R between topographic characterization parameters Sa with Sdq, Vvv, and Sz versus scale.

wavelengths from 9 to 400 μm. The bandpass filter is described above. For simplicity, the factor of four is omitted in the calculations here. This omission does not affect the correlation strengths; it simply shifts the parameter values on the abscissa.

After bandpass filtering at all the central wavelengths, three kinds of conventional characterization (ISO 25178-2:2021) were calculated. The first four statistical moments of height, Sa, Sq, Ssk, Sku are used, along with the maximum height, Sz. Second, the hybrid parameters (root mean square gradient, or slope, and developed area ratio), Sdq and Sdr introduce spatial components. Third, the volume parameters, based on the Abbott curve, Vmp, Vmc, Vvc, and Vvv, use default values, as defined in ISO 25178-3, 10% for Vmp, 10% and 80% for Vmc and Vvc, and 80% for Vvv.

2.2. Multiscale regression analyses and functional correlations

Multiscale, linear regression analyses were performed to evaluate the strength of the correlations of each of the surface texture parameters, described above, had with the friction. Coefficients of determination (R^2) were calculated for each parameter and each scale. These R^2 values were plotted versus the respective scale at which they were calculated, where the scale is the value of the central wavelength. In addition, cross correlations between the characterization parameters were examined as a function of scale. A general description of the bandpass multiscale procedure is given in figure 2.

3. Results

Filtered measurements are shown in figure 3. These illustrate one surface with a progression of three central wavelengths and S-F filtering.

Figure 4 shows two surfaces with S-F filtering and bandpass filtering at 9 μm. Some extreme peaks and valleys are apparent in the renderings, particularly with the 9 μm bandpass filter in figures 4(a) and (b).

Table 1. Pin surfaces and friction coefficients, μ (Berglund *et al* 2010a, Berglund *et al* 2010b).

Pin *Material* *Finish milling*	GGG70L		Carmo		Sleipner	
	Fine	Rough	Fine	Rough	Fine	Rough
Mean friction coefficient (μ)	0.140	0.150	0.133	0.141	0.137	0.161

Table 2. Coefficient of determination ($R^2 \times 100$), friction with parameters and scales.

Filters\parameters	Sa	Sq	Ssk	Sku	Sz	Sdq	Sdr	Vmp	Vmc	Vvc	Vvv
R^2cv	20	20	11	10	60	71	73	1.0	17	16	39
R^2bp	95	93	13	13	90	92	92	70	84	89	92
Scale	25	18	141	141	18	25	25	9	25	18	25

S-Ffilter: R^2cv; strongest correlations with bandpass filter: R^2bp; scales are μm.

They appear as spikes and their origin is not known. Regardless, they have a strong influence on Sz, and less on the other parameters.

The results of regression analyses between the friction coefficient and Sa are shown in figure 5 for three bandpass filters. The magnitude of Sa clearly increases with the scale of the bandpass. The importance of scale in finding strong correlations is clear. The scale of the strongest correlation is 25 μm. At 100 μm there is essentially no correlation between the friction coefficient and Sa.

For the calculated parameters after bandpass filtering, the strongest correlations and the corresponding scales are shown in table 2, along with the correlations for S-F filtering. Seven out of eleven of the correlations using the bandpass filters have R^2 values over 0.8, all at scales of either 18 or 25 μm (table 2). The S-F filtering R^2 values were all below 0.4, except Sdq and Sdr, which were 0.71 and 0.73 respectively. This agrees with the earlier result from Berglund *et al* (2010a). The height parameters, Sa and Sq, appear to be sensitive to the larger wavelengths in the S-F filtered surfaces. The developed surface area, Sdr, and the rms slope, Sdq, are calculated at the scale of the sampling interval. These two parameters show correlations with friction with S-F filtering that are several times stronger than most of the other parameters. All the correlations are higher with some kind of bandpass filtering. Friction never correlates well with the skew and kurtosis, Ssk and Sku, or with the maximum peak-to-valley roughness, Sz. The latter could be attributed to influence of the spikes that were noted in renderings in figures 3 and 4. These observations support the contention that finding strong functional correlations depends on selecting appropriate characterization parameters.

Trends of the correlations between friction and one of each of the characterization parameters that showed the strongest correlations are shown in figure 6. The trends are smooth with respect to scale. A clear maximum is shown at 25 μm. At larger scales, the correlation strength decreases suddenly to near zero. This is consistent with earlier results for a different kind of bandpass filter (Berglund *et al* 2010a) and confirms the importance of selecting the appropriate scale in finding strong functional correlations.

Figure 7 shows correlation strengths using the correlation coefficient, R, versus scales, between a height and a hybrid parameter (Sa and Sdq), between a height and a volume parameter (Sa and Vvv), and between two height parameters (Sa and Sz). The correlations are strong across all scales except for Sa and Sz at the scales below 50 μm. At the finest scale, the correlation between these two height parameters even becomes negative. (Nowicki 1985) found an R value of 0.963 between the average roughness and peak to valley roughness for profiles from ground surfaces. Strong correlations are found between Sa and Sz here at the largest scales with conventional filtering. The increasing weakness of correlation between Sa and Sz as scales diminish and becoming negative is perhaps worthy of note and followup, beyond the scope of this paper.

The strength of the cross correlations obviously should depend on the nature of the topography being studied, as well as on the nature of the parameters. The dependence of the strength of the cross correlation on scale has not, to our knowledge, been studied previously. The weak correlations between Sa and Sz, noted here at the fine scales, might be associated with the presence of spikes, which can be seen at the fine scales in the renderings in figures 3 and 4. These spikes would influence the maximum peak-to-valley, Sz, much more than they would the arithmetic average, Sa. The scales of weak correlation between Sa and Sz are also the scales where the friction correlated strongly with Sa.

4. Discussion

Multiscale characterization and regression analyses using several parameters, as done here, can facilitate the discovery of the appropriate scales, parameters, and measurements. This work builds on analyses of the same data previously used by Berglund *et al*

(Berglund *et al* 2010a, Berglund *et al* 2010b) that demonstrated the value of multiscale geometric analyses in discovering strong functional correlations. That previous work relied on special algorithms for the bandpass filters, which were not rigorously defined mathematically and are unavailable. The current work demonstrates a practical method for multiscale analysis.

Correlation is not necessarily causation. A chain of calculated dependencies may or may not be apparent in any given case. The significance of the correlations observed here is worthy of further consideration. Fundamental topographic interactions during sliding contact include plowing and burnishing. These kinds of interactions suggest that the slopes of surface features characterized by the hybrid parameters Sdq and Sdr are inherently preferable to height parameters as geometrically pertinent topographic characterizations. Strengths of the cross correlations between the parameters indicates that they lack independence (Nowicki 1985). The interaction of peaks on the dies with the sheet metal in the friction experiments points to the importance of the height and volume parameters in this case. The spatial distribution of these peaks can, logically, be important, suggesting the importance of the developed area, Sdr, and slope, Sdq.

In tribology geometries of the shapes of contacting surface features determine the topographical components of contact behavior. The hybrid parameters Sdq and Sdr characterize average slopes at the sampling interval. Both slopes and surface areas naturally vary with scale on irregular topographies (Bartkowiak *et al* 2024). They are highly correlated, geometrically one cannot change independently of the other. They are both calculated scale of the sampling interval. The filtering used here has modified the topograhic data at the scale of the sampling interval, hence their response to bandpass filters. The utility of Sdq and Sdr is demonstrated by their strong correlation with friction coefficients.

The observation that many parameters exhibit the strongest correlation at central wavelengths of about 18 or 25 μm, suggests that this might be the scale range of some physical interactions between the surfaces that influences the friction. These are about the same ranges found in Berglund *et al* (2010a) for conventional parameters and specialized bandpass filtering. For the same friction and topographic data, the strongest correlations ($R^2 \sim 0.9$) versus relative areas, which is a kind of lowpass filter, were found at 10 μm, and versus area-scale complexity, which is a kind of bandpass filter were at 200 μm (Berglund *et al* 2010b). The discrepancies in scales of strongest correlations could indicate that these scales depend somewhat on the nature of the topographic characterization parameters.

Surface slopes have appeal in their nature as pertinent topographic characterizations for correlating with friction in this system. Steeper slopes on the machined tool logically would provide resistance to sheet metal sliding over it. Averages, mean and RMS, would seem like more appropriate statistics than skew or kurtosis. This supposition is supported by the strong correlations found with Sdq and Sdr. Previously it was shown that these parameters correlate well with each other. Although average roughness, Sa, and other height parameters like, Sq and Sz, when calculated with S-F filtering often are inadequate for finding correlations when used with this broader bandwidth, although they work well here with narrow bandwidths. This might be because when bandpass filters are narrow enough, height parameters are indicative of slopes on the surface, $\Delta y/\Delta x$. This is supposing that narrow wavelengths approach an effective Δx and the height values are Δy This supposition is supported by the strong correlations between Sa and Sq over all scales (figure 6). Slopes on measured surfaces contribute to uncertainties in measurements as well (Lemesle 2023a, 2023b).

The basic principles for surface metrology to facilitate finding functional correlations are supported (Brown *et al* 2018 and Brown 2021). Functional correlations can guide dimensioning and tolerancing of surface topographies. Measurements and characterizations at the appropriate scales and appropriate characterization parameters were proposed as two axioms, scale and characterization. Two corollaries were also proposed, measurements—of sufficient quality, and statistics—appropriate for the application (Brown 2021).

Bandpass filtering strengthens correlations with friction for all the parameters in this study as is shown by the results of numerous multiscale regression analyses here. For conventional filtering and the hybrid parameters, Sdq and Sdr, and R^2 values of 0.71 and 0.73, are found respectively. Both of these are calculated conventionally in a narrow scale ranges near the sampling interval, rather than over the normal range of S-F filtering like the height parameters.

In summary, a novel method to create these bandpass filters using commercial software has been demonstrated. Strong correlations between tribological functional behavior and friction on different scales have been identified. This method is effective for analyzing the functional behavior of surface topographies on a multiscale basis.

This approach makes it possible to perform multiscale regression analyses and discover functional correlations that can facilitate the specification of topographies in product design, and of processes in manufacturing, without specialized software. The proposed method produces results that are comparable to specialized approaches from the literature.

Fundamental interactions, and the utility of multiscale topographic characterization parameters in characterizing them, are specific to certain, relatively narrow bandwidths compared to the broader bandwidths used traditionally for typical roughness characterizations. Therefore, topographic characterizations using these broader, more typical bandwidths typically fail to find strong functional correlations because they fail to adapt to the scale specificity available in multiscale characterizations that can match those of discrete fundamental interactions that aggregate to synthesize macroscopic topographically dependent phenomena, like friction (Brown 2021).

5. Conclusions

1. Conventional height and hybrid parameters can be applied to bandpass filtered measurements for finding richness in strong characterizations using multiscale regression analyses.
2. Bandpass filtering strengthens the functional correlation with friction for all the parameters in this study.
3. Coefficients of determination R^2 of friction with Sa, Sq, Sdq, Sdr, and Vvv exceed 0.9 at specific scales after spectral decomposition.
4. Sdq and Sdr, average slope and developed area ratio, had the strongest correlations with conventional S-F filtering, yielding R^2 values of 0.71 and 0.73, respectively.
5. The four basic principles for facilitating discoveries of strong functional correlations, as proposed by Brown (2021), i.e., appropriate scales, pertinent characterizations, sufficient measurement capability, and appropriate statistics, are reinforced here.

Acknowledgments

The authors thank Prof Niels O Bay, Department of Mechanical Engineering, Technical University of Denmark for the friction testing and use of those data, John Ryan O'Neill, Yifan Shao, Edmund Resor, and Ed Resor for work on analyses and figures, Mary Kathryn Thompson for her critiques, and Marilyn Cochran Brown for proofreading.

Data availability statement

The data cannot be made publicly available upon publication because the cost of preparing, depositing and hosting the data would be prohibitive within the terms of this research project. The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iDs

Christopher A Brown https://orcid.org/0000-0002-9355-4824
François Blateyron https://orcid.org/0000-0001-7048-4045
Johan Berglund https://orcid.org/0000-0003-3656-1806
Adam J Murrison https://orcid.org/0009-0008-5973-1453
Jack Jacob Jeswiet https://orcid.org/0000-0003-2407-0356

References

Agunwamba C 2010 A MATLAB Program to implement the band-pass method for discovering relevant scales in surface roughness measurement *Masters thesis* Worcester Polytechnic Institute

Allwood J M, Duncan S R, Cao J, Groche P, Hirt G, Kinsey B, Kuboki T, Liewald M, Sterzing A and Tekkaya A E 2016 Closed-loop control of product properties in metal forming *CIRP Ann.* **65** 573–96

Andreasen J, Olsson D D, Chodnikiewicz C and Bay N 2006 Bending under tensiontest with direct friction measurement *Proc. Inst. Mech. Eng.* B **220/1** 73–80

ASME B46.1 2019 Surface Texture (Surface Roughness, Waviness, and Lay) An International Standard, American Society of Mechanical Engineers, New York. Appendix k 118–25

Axinte D A, Gindy N, Fox K and Unanue I 2004 Process monitoring to assist the workpiece surface quality in machining *Int. J. Mach. Tools Manuf* **44** 1091–108

Bartkowiak T, Berglund J and Brown C A 2018 Establishing functional correlations between multiscale areal curvatures and coefficients of friction for machined surfaces *Surf. Topography: Metrol. Prop.* **6** 034002

Bartkowiak T, Etievant D and Brown C A 2024 Multiscale slope anlysis and functional correlation with gloss reflectance from photographic paper *Surf. Topography: Metrol. Prop.*

Bay N, Azushima A, Groche P, Ishibashi I, Merklein M, Morishita M, Nakamura T, Schmid S and Yoshida M 2010 Environmentally benign tribo-systems for metal forming *CIRP Ann.* **59** 760–80

Bay N, Olsson D D and Andreasen J L 2008 Lubricant test methods for sheet metal forming *Tribol. Int.* **41** 844–53

Berglund J, Wiklund D and Rosén B -G 2011 A method for visualization of surface texture anisotropy in different scales of Observation *Scanning* **33** 325–31

Berglund J, Agunwamba C, Powers B, Brown C A and Rosén B -G 2010a On discovering relevant scales in surface roughness measurement—an evaluation of a band-pass method *Scanning* **32** 244–9

Berglund J, Brown C A, Rosén B-G and Bay N 2010b Milled die steel surface roughness correlation with steel sheet friction *CIRP Ann.* **59** 577–80

Blateyron F 2017 New sliding bandpass filters for multiscale exploration of surface texture *Int. Conf. Met&Props of Eng. Surf.*

Brown C A 2021 Surface metrology principles for snow and ice friction studies *Frontiers in Mechanical Engineering* **7**

Brown C A, Charles P D, Johnsen W A and Chesters S 1993 Fractal analysis of topographic data by the patchwork method *Wear* **161** 61–7

Brown C A, Johnsen W A and Charles P D 1994 Method of quantifying the topographic structure of a surface *U.S. Patent* No. 5,307,292 U.S. Patent and Trademark Office

Brown C A *et al* 2018 Multiscale analyses and characterizations of surface topographies *CIRP Ann.* **67** 839–62

Brown C A and Savary G 1991 Describing ground surface texture using contact profilometry and fractal analysis *Wear* **141** 211–26

De Chiffre L, Lonardo P, Trumpold H, Lucca D A, Goch G, Brown C A, Raja J and Hansen H N 2000 Quantitative characterisation of surface texture *CIRP Ann.* **49** 635–52

Deltombe R, Bigerelle M and Jourani A 2015 Analysis of the effects of different machining processes on sealing using multiscale topography *Surf. Topography: Metrol. Prop.* **4** 015003

Denkena B, Böß V, Nespor D and Samp A 2011 Kinematic and stochastic surface topography of machined TiAl6V4-parts by means of ball nose end milling *Procedia Engineering* **19** 81–7

Denkena B, Böß V, Nespor D, Gilge P, Hohenstein S and Seume J 2015 Prediction of the 3D surface topography after ball end milling and its influence on aerodynamics *Procedia CIRP* **31** 221–7

Guibert R, Hanafi S, Deltombe R, Bigerelle M and Brown C A 2020 Comparison of three multiscale methods for topographic analyses *Surf. Topography: Metrol. Prop.* **8** 024002

Goïc G L, Bigerelle M, Samper S, Favrelière H and Pillet M 2016 Multiscale roughness analysis of engineering surfaces: a comparison of methods for the investigation of functional correlations *Mech. Syst. Sig. Process.* **66–67** 437–57

ISO 25178-2 2021 Geometrical product specifications (GPS) - Surface texture: Areal - Part 2: Terms, definitions and surface texture parameters International Organization for Standardization

ISO 16610-21 2011 Geometrical product specifications (GPS) - Filtration - Part 21: Linear profile filters: Gaussian filters International Organization for Standardization

ISO 16610-61 2015 Geometrical product specification (GPS) - Filtration - Part 61: Linear areal filters – Gaussian filters International Organization for Standardization

Lavernhe S, Quinsat Y, Lartigue C and Brown C 2014 Realistic simulation of surface defects in five-axis milling using the measured geometry of the tool *Int. J. Adv. Manuf. Technol.* **74** 393–401

Leach R K, Giusca C L, Haitjema H, Evans C and Jiang X 2015a Calibration and verification of areal surface texture measuring instruments *CIRP Ann.* **64** 797–813

Leach R, Evans C, He L, Davies A, Duparré A, Henning A, Jones C W and O'Connor D 2015b Open questions in surface topography measurement: a roadmap *Surf. Topography: Metrol. Prop.* **3** 013001

LeGoic G, Favreliere H, Samper S and Formosa F 2011 Multi scale modal decomposition of primary form, waviness and roughness of surfaces *Scanning* **33** 332–41

Lemesle J, Moreau C, Deltombe R, Martin J, Blateyron F, Bigerelle M and Brown C A 2023a Height fluctuations and surface gradients in topographic measurements *Materials* **16** 5408

Lemesle J, Moreau C, Deltombe R, Blateyron F, Martin J, Bigerelle M and Brown C A 2023b Top-down determination of fluctuations in topographic measurements *Materials* **16** 473

Mandelbrot B 1967 How long is the coast of Britain? statistical self-similarity and fractional dimension *Science* **156** 636–8

Mandelbrot B 1975 Les objets fractals: forme, hasard et dimension, coll *Nouvelle Bibliotheque scientifique* (Flammarion) 1975

M'Saoubi R, Axinte D, Soo S L, Nobel C, Attia H, Kappmeyer G, Engin S and Sim W-M 2015 High performance cutting of advanced aerospace alloys and composite materials *CIRP Ann.* **64** 557–80

Nowicki B 1985 Multiparameter representation of surface roughness *Wear* **102** 161–76

Savio E, De Chiffre L, Carmignato S and Meinertz J 2016 Economic benefits of metrology in manufacturing *CIRP Ann.* **65** 495–8

Schmitt R H, Peterek M, Morse E, Knapp W, Galetto M, Härtig F, Goch G, Hughes B, Forbes A and Estler W T 2016 Advances in large-scale metrology—review and future trends *CIRP Ann.* **65** 643–65

Schulze V, Bleicher F, Groche P, Guo Y B and Pyun Y S 2016 Surface modification by machine hammer peening and burnishing *CIRP Ann.* **65** 809–32

Shao Y, Xu F, Chen J, Lu J and Du S 2023 Engineering surface topography analysis using an extended discrete modal decomposition *J. Manuf. Processes* **90** 367–90

Shivpuri R and Semiatin S L 1992 Friction and wear of dies and die materials *ASM International, ASM Handbook* **18** 621–48

VDA 2007 *Geometrical Product Specifications, Surface Texture - Definitions and Characteristic Values of the Dominant Waviness* (Verband der deutschen Automobilindustrie e. V. (VDA)) Frankfurt/M. (02/2007)

Vollertsen F, Biermann D, Hansen H N, Jawahir I S and Kuzman K 2009 Size effects in manufacturing of metallic components *CIRP Ann.* **58** 566–87

Vulliez M, Gleason M A, Souto-Lebel A, Quinsat Y, Lartigue C, Kordell S P, Lemoine A C and Brown C A 2014 Multi-scale curvature analysis and correlations with the fatigue limit on steel surfaces after milling *Procedia CIRP* **13** 308–13