Institute of Physics Publishing | Measurement Science and Technology
Meas. Sci. Technol. **13** (2002) 1924–1930 | PII: S0957-0233(02)34773-8

Ambiguities in the definition of spacing parameters for surface-texture characterization

Richard K Leach[1] **and Peter M Harris**[2]

[1] Centre for Basic, Thermal and Length Metrology, National Physical Laboratory,
Queens Road, Teddington, Middlesex TW11 0LW, UK
[2] Centre for Mathematics and Scientific Computing, National Physical Laboratory,
Queens Road, Teddington, Middlesex TW11 0LW, UK

Received 12 March 2002, in final form 10 July 2002, accepted for publication 17 September 2002
Published 1 November 2002
Online at stacks.iop.org/MST/13/1924

Abstract
A range of instruments is available for surface-texture measurement. The instruments record the (x, z) coordinates of data points that represent a surface profile, and apply software to filter the data and compute various surface-texture parameters that aim to describe the properties of the surface. However, many current and proposed parameters are not unambiguously defined. The focus of this paper is on one such parameter, namely, the spacing parameter RSm. It is shown that the definition of the RSm parameter given in standards is ambiguous, leading to the possibility of different algorithms for calculating RSm whose implementations can give results that differ considerably. Results obtained from three algorithms for calculating RSm applied to a real measurement data set are presented.

Keywords: surface-texture measurement, spacing parameters, traceability

1. Introduction

Knowledge of the topography of a machined surface is necessary in order to understand the functional performance of a surface, and is consequently essential to the manufacturing process. The use of a parameter to associate a numerical value to the measured topography of a surface was proposed many years ago (e.g. Hume (1980) gives a brief history). A single numerical value allows different surfaces to be readily compared and facilitates the interpretation of surface-texture tolerances on engineering drawings. Subsequently there has been a proliferation in the number of parameters that have been adopted by the various standards bodies (Whitehouse 1982). The current ISO specification standard (ISO 4287 1997) lists 11 parameters for two-dimensional (profile) measurements, nine of which are calculated from profile height data (z-values), one from profile spacing data[3] (x-values) and one that is a hybrid of height and spacing data.

Communicating information about a surface using a defined set of surface-texture parameters is effective only if those parameters have *unambiguous* mathematical definitions. Without such definitions there is scope for different interpretations of how the parameters should be calculated and, consequently, the danger that different software engineers would design (mathematically) different algorithms to calculate the parameters. The spacing parameter RSm (ISO 4287 1997) would appear to be an example of a parameter for which such an ambiguity exists, and is the subject of this paper. It is not the intention here to single out the problems associated with the definition of this particular parameter, but to use the RSm parameter to highlight the generic problems associated with defining surface-texture parameters. Note that the mathematical ambiguities inherent in the definition of RSm also apply to the spacing parameters defined in older specification standards (including previous versions of ISO 4287), such as the peak count *Pc*, the mean spacing of profile irregularities *Sm*, the mean spacing of local peaks of a profile *S*, and the high spot count *HSC* (see Leach (2001, appendix A)).

Ambiguities in the definitions of surface-texture parameters can lead to serious problems in ensuring *traceability* of

---

[3] The definition also requires the measurement of a height parameter—see section 2.

surface-texture measurement as well as in interpreting the functionality of a surface. A related problem, not addressed here, is that without a statement of uncertainty for a calculated surface-texture parameter it is difficult to assess whether the difference in the results obtained from two algorithms for calculating the same parameter is critical to understanding the surface being measured.

The problem of ambiguity extends to three-dimensional surfaces. A recent EC-funded project (SURFSTAND 2001) carried out significant research for three-dimensional surface characterization. One aim of the project was to produce a suite of parameters for three-dimensional measurements that would form the basis of a three-dimensional version of ISO 4287 (1997) by 2003 (see (Stout and Blunt 2000). The resultant draft suite of parameters contains five height parameters, four spatial parameters, three hybrid parameters and six parameters that are explicitly designed to represent the functionality of a surface. Clearly these newer parameters will also require unambiguous mathematical definitions.

This paper is organised as follows. The terms required to define the spatial surface-texture parameter RSm are described in section 2, with a discussion of these terms in section 3. In section 4 the design of an algorithm for calculating RSm is described, and highlights how ambiguity in the definition of RSm leads to different algorithmic approaches. In sections 5 and 6 results are presented and indications given about the problems of having more than one interpretation of a parameter. In section 7 the results are discussed, and section 8 contains concluding remarks.

2. Terms required for the definition of the spacing parameter RSm

In order to understand the RSm parameter it is necessary to present a number of terms, such as 'roughness profile', 'sampling length', 'discrimination' and 'profile element'. ISO 4287 (1997) states definitions of these terms and the RSm parameter and the terms are described below. The clause of ISO 4287 relating to each term is indicated in square brackets, and where a direct quote is taken from the relevant clause of the standard this is in italics.

Primary profile [Clause 3.1.5]

ISO 4287 refers to ISO 3274 (1996) [Clause 3.1.4]. *Total profile after application of the short wavelength filter* λs. For stylus-based surface-texture measuring instruments the finite size of the stylus is the reason for the rejection of very short wavelengths. In practice, this mechanical filtering effect is often used by default for the λs filter (Leach 2001).

Roughness profile [Clause 3.1.6]

The *profile derived from the primary profile by suppressing the longwave component using the profile filter* λc. The filter is a long wavelength (high pass) filter (ISO 11562 1996) with a cut-off wavelength λc. The roughness profile is the basis for the evaluation of roughness profile parameters, or R-parameters.

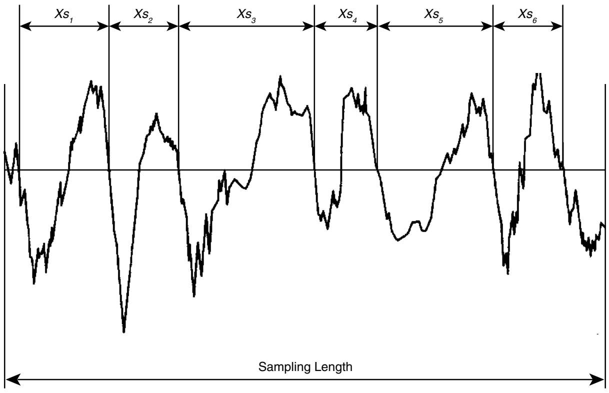

Figure 1. Width of profile elements, from ISO 4287 (1997).

Mean line for the roughness profile [Clause 3.1.8.1]

The *line corresponding to the longwave profile component suppressed by the profile filter* λc. The mean line is the x-axis, i.e., the line $z = 0$, for the roughness profile.

Sampling length lr [Clause 3.1.9]

The *length in the direction of the x-axis used for identifying the irregularities characterizing the profile under evaluation.* The sampling length for roughness is equal to the cut-off wavelength of the profile filter λc.

Profile peak [Clause 3.2.4]

An outwardly directed (from material to surrounding medium) portion of the assessed profile connecting two adjacent points of the intersection of the profile with the x-axis. A profile peak is a part of the profile above the mean line (but see height and spacing discrimination below).

Profile valley [Clause 3.2.5]

An inwardly directed (from surrounding medium to material) portion of the assessed profile connecting two adjacent points of the intersection of the profile with the x-axis. A profile valley is a part of the profile below the mean line (but see height and spacing discrimination below).

Height and spacing discrimination [Clause 3.2.6]

The *minimum height and minimum spacing of profile peaks and profile valleys of the assessed profile which should be taken into account.* Only features with a height and width larger than specified values are counted (see figure 1).

Profile element [Clause 3.2.7]

A *profile peak and the adjacent profile valley* (after height and spacing discrimination).

Profile element width Xs [Clause 3.2.13]

The *length of the x-axis segment intersecting with the profile element* (see figure 1).

Maximum height of the roughness profile Rz [Clause 4.1.3]

The *sum of the height of the largest profile peak height Rp and the largest profile valley depth Rv within a sampling length.*

Mean width of the roughness profile elements RSm [Clause 4.3.1]

The *mean value of the profile element widths Xs within a sampling length.* The parameter requires height and width discrimination (as described above). ISO 4287 (1997) recommends that, in the absence of other specifications, a profile peak or valley is considered to be real if both the following conditions are met:

(a) its height exceeds 10% of the Rz parameter value, and
(b) its width exceeds 1% of the sampling length lr.

Finally, it is normal practice to evaluate surface-texture parameters by averaging the values obtained over several successive sampling lengths. ISO 4288 (1996) recommends the use of five sampling lengths as the default for roughness evaluation.

3. Discussion of the terms required for the definition of the spacing parameter RSm

Before any attempt is made to construct an algorithm to calculate the parameter, a number of comments should be made about terms and definitions.

For the purpose of undertaking height discrimination, the calculation of RSm depends on calculating the amplitude parameter Rz which itself needs to be unambiguously defined. There is potential for some inconsistency as it is possible (although perhaps unlikely) that the profile peak or valley that determines Rz is subsequently 'ignored' in the calculation of RSm because its width fails the discrimination test on spacing.

The definition of RSm given in Clause 4.3.1 of ISO 4287 (1997) is given in terms of the profile element widths Xs within a sampling length lr

$$RSm = \frac{1}{N}\sum_{i=1}^{N} Xs_i,$$

where N is the number of profile elements and Xs_i is the width of the ith profile element. Clearly, an equivalent formula for RSm is

$$RSm = \frac{1}{N}d,$$

where d is the distance along the mean line of the roughness profile between the left-hand endpoint of the first profile element and the right-hand endpoint of the last profile element (figure 1). The latter formula for RSm suggests that the critical quantities for its calculation are the positions of these endpoints and the number of profile elements between the endpoints. This is in contrast to the former formula, which involves *individual* profile widths Xs_i. *Any ambiguity* in deciding the positions of the endpoints or counting the number of profile elements can be expected to lead to ambiguity in RSm. Figure 1 indicates that such an ambiguity can exist: there are three places where the roughness profile shown intersects the mean line close to the left-hand endpoint of the profile. The most interior of these has been chosen because of the threshold to define the left-hand endpoint of the first profile element.

If a surface-texture parameter is to convey useful information about a surface, it is desirable that an algorithm for calculating the value of the parameter from experimental data possesses a number of properties, including the following:

- *stability* (i.e. small changes to the data cause small changes in the value of the parameter),
- *smoothness* (i.e. smooth changes to the data and other quantities, such as the threshold values for discrimination, cause smooth changes in the value of the parameter), and
- *invariance* (i.e. the value of the parameter is essentially unchanged with respect to transformations of the data, such as reversal and inversion).

However, in its present form the definition of RSm would appear to make it difficult to design an algorithm with these properties because, for example, for a profile with a number of peaks and valleys with heights close to the height discrimination threshold, a small change in the threshold (equivalently to Rz) can be expected to cause 'significant jumps' in the number of profile elements. Consequently, the value for RSm obtained for a given surface (and using a given algorithm) can depend critically on factors such as the particular part of the surface chosen for analysis.

4. An algorithm for calculating RSm

In order to calculate a value for RSm it is necessary to translate the terms and definition of RSm given in section 2 into an *algorithm* suitable for implementation as software. An algorithm is proposed below for calculating a value of RSm for a roughness profile defined by points (x_i, z_i), $i = 1, \ldots, m$, with $x_1 < x_2 < \cdots < x_m$, within a sampling length lr and with maximum height Rz.

Since the parameter RSm is defined in terms of profile element widths Xs, the basis of the algorithm is the identification of zero crossing points (i.e. intersections of the profile with the x-axis or mean line). A set of zero crossing points is determined so that the peaks and valleys defined by these points satisfy the height and spacing discrimination tests. It is not claimed that this is the only approach to implementing discrimination and evaluating RSm, but it arguably follows naturally from the terms and definitions given in section 2.

Step 1. Determine *all* the zero crossing points c_k for the profile. This is done by identifying indices k for which $z_k z_{k+1} \leqslant 0$ and linearly interpolating between (x_k, z_k) and (x_{k+1}, z_{k+1}) to obtain the zero crossing point $x = c_k$ (corresponding to $z = 0$) in the interval $[x_k, x_{k+1}]$. Let the crossing points so determined be c_k, $k = 1, \ldots, K$, with $c_1 < c_2 < \cdots < c_K$.

Step 2. For each pair of adjacent zero crossing points c_k and c_{k+1}, apply *discrimination* to determine whether the part of the profile between c_k and c_{k+1} defines a real peak or valley. Where this part of the profile fails the discrimination tests, replace the two zero crossing points by a single zero crossing point, renumber the remaining zero crossing points and reduce K by one.

Note. There are a number of ways the two zero crossing points may be replaced by a single point, for example, by replacing c_k and c_{k+1} with (A) c_k, or (B) c_{k+1}, or (C) the mean[4] of c_k and c_{k+1}. It is necessary to *specify* how this is to be done if the algorithm is to be implemented in software unambiguously. Implementing (A), (B) or (C) can affect the final number of crossing points identified and hence the number N of profile elements. For example, consider a roughness profile for which each peak and valley satisfies the discrimination condition on height and with three crossing points c_{k-1}, c_k and c_{k+1} for which

$$c_k - c_{k-1} < \delta_s, \qquad c_{k+1} - c_k < \delta_s, \qquad c_{k+1} - c_{k-1} > \delta_s,$$

where δ_s is the threshold for discrimination on spacing. Applying approach (A), the three crossing points are replaced by the two crossing points c_{k-1} and c_{k+1}. Applying approach (B), however, they are replaced by the single crossing point c_{k+1}.

Step 3. Ensure alternation of the profile peaks and valleys. Where a profile peak (valley) is adjacent to another peak (valley), combine the features into one by removing their common crossing point, renumber the remaining zero crossing points and reduce K by one.

Note. A profile peak (valley) is considered to be a part of the roughness profile between two zero crossing points for which the z-value of the maximum absolute value lies above (below) the mean line. Other characterizations of a profile peak (valley) may be used, e.g., requiring that the number of z-values lying above (below) the mean line exceed the number lying below (above), suggesting further ambiguities in the calculation of RSm.

Step 4. Determine the number N of complete profile elements within the sampling length

$$N = \frac{L-1}{2},$$

where L is the largest odd integer less than or equal to K.

Step 5. Determine the distance d along the mean line of the roughness profile between the left-hand endpoint of the first profile element and the right-hand endpoint of the last profile element

$$d = c_L - c_1.$$

Note. For the case that $L = K$ (K odd), there is no ambiguity in defining d in this way. However, for the case that $L < K$ (K even), the interval between c_2 and c_{L+1} will also contain N complete profile elements and d is calculated from

$$d = c_{L+1} - c_2.$$

These alternatives suggest a further ambiguity in the definition of RSm. In what follows, the start of the first profile element is always taken to be c_1 and d is calculated using the first formula.

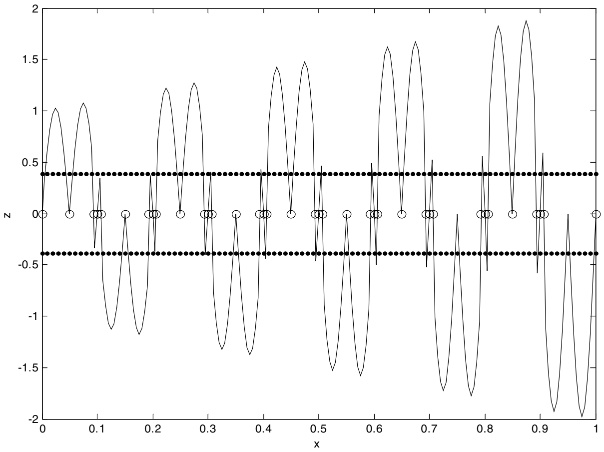

Figure 2. Simulated test data set with a complete set of zero crossing points (small circles). The two sets of 'discs' indicate the thresholds for discrimination.

Step 6. Determine the value of the RSm parameter

$$RSm = \frac{1}{N} d.$$

Apart from the decisions to be made in steps 2, 3 and 5, the above steps define an *algorithm* for calculating the RSm parameter that can be (straightforwardly) implemented as software.

5. Results for the test data

To illustrate the operation of the algorithm described in section 4 consider the simulated test data set (or *softgauge*) shown in figure 2. The data set is based on a damped sinusoidally shaped roughness profile with additional zero crossing points introduced to test the discrimination parts (steps 2 and 3) of the algorithm. The complete set of zero crossing points for the profile, corresponding to the output of step 1, is marked by small circles, together with an indication of the thresholds for discrimination. For the latter, two sets of 'discs' are shown at plus and minus the height threshold and separated in the horizontal direction by amounts equal to the spacing threshold.

Figure 3 shows the simulated test data set together with the (reduced) set of zero crossing points, corresponding to the output of step 3, used to define the roughness profile elements. Here, c_k and c_{k+1} are replaced by the mean of c_k and c_{k+1} (step 2, choice (C)), where this is necessary.

It is clear that neighbouring zero crossing points that define 'spurious' elements are replaced by a single zero crossing point, and neighbouring peaks and valleys are coalesced into single features. At the left-hand end of the profile the spurious elements fail both the height and spacing discrimination tests; at the right-hand end the elements fail only the spacing discrimination test. The algorithm identifies $N = 5$ profile elements within the interval [0, 1] of length $d = 1$. Therefore, the value computed for RSm is 0.20 (which can be verified by inspection as being a reasonable[5] value for this profile).

---

[4] Algorithm (C) is not a strict implementation of the Standard because an end of a profile element may not be a zero crossing point of the profile. However, it is included as being intermediary to algorithms (A) and (B), and as an attempt to define an algorithm with better invariance properties compared with algorithms (A) and (B).

[5] Without an unambiguous definition of RSm it is not possible to claim that this value is the *correct* value.

Table 1. Values of RSm for the roughness profile shown in figure 4. Values are given for five non-overlapping sampling lengths using the three algorithms (**A**, **B** and **C**). Each algorithm is applied to the data ordered from left to right (i.e. in the 'forward' direction (f)) and to the data from right to left (i.e. in the 'backward' direction (**b**)).

	Sample 1 ($Rz = 1.24\ \mu$m)			Sample 2 ($Rz = 1.14\ \mu$m)			Sample 3 ($Rz = 1.33\ \mu$m)			Sample 4 ($Rz = 1.07\ \mu$m)			Sample 5 ($Rz = 1.36\ \mu$m)			
	N	d (μm)	RSm (μm)	N	d (μm)	RSm (μm)	N	d (μm)	RSm (μm)	N	d (μm)	RSm (μm)	N	d (μm)	RSm (μm)	Mean (μm)
A (f)	12	792	66	12	757	63	9	743	83	12	720	60	12	740	62	**67**
B (f)	9	792	88	10	721	72	8	751	94	10	724	72	10	739	74	**80**
C (f)	11	792	72	11	759	69	9	749	83	11	722	66	11	739	67	**71**
A (b)	12	792	66	11	717	65	9	721	80	11	777	71	12	739	62	**69**
B (b)	10	792	79	10	757	76	8	721	90	10	770	77	9	740	82	**81**
C (b)	11	792	72	11	759	69	8	721	90	11	772	70	9	739	82	**77**

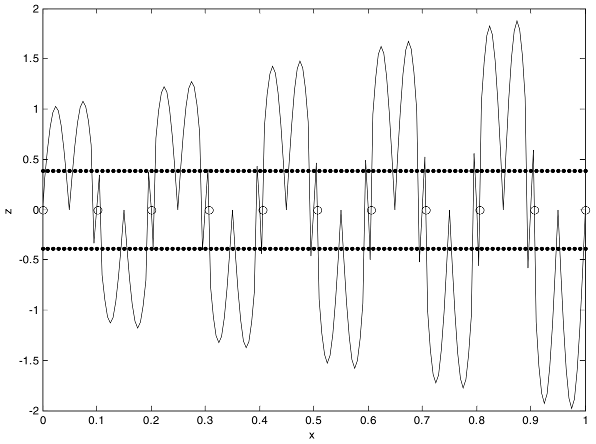

Figure 3. Simulated test data set with the reduced set of zero crossing points used to compute the roughness profile element widths Xs.

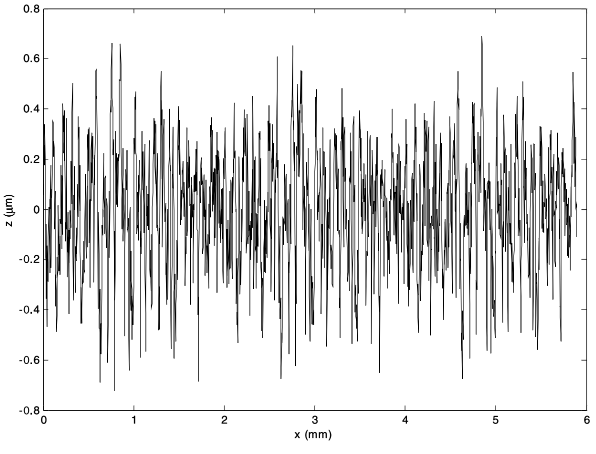

Figure 4. Measurement data set after application of a Gaussian filter to extract the roughness profile.

The values returned for RSm using the other implementations (A and B) of step 2 of the algorithm are also 0.20. This indicates that *for this simulated data set* it is not critical which of the three proposed algorithms is used.

6. Results for the measurement data

The operation of the algorithm described in section 4 is now illustrated using a real measurement data set. Figure 4 shows the *roughness* profile obtained following application of a Gaussian filter with cut-off wavelength $\lambda c = 0.8$ mm to the measurement data.

In rows 2–4 of table 1 are given the calculated values for N, d and RSm for five (non-overlapping) sampling lengths of the filtered data set (each of sampling length $lr = 0.8$ mm) for

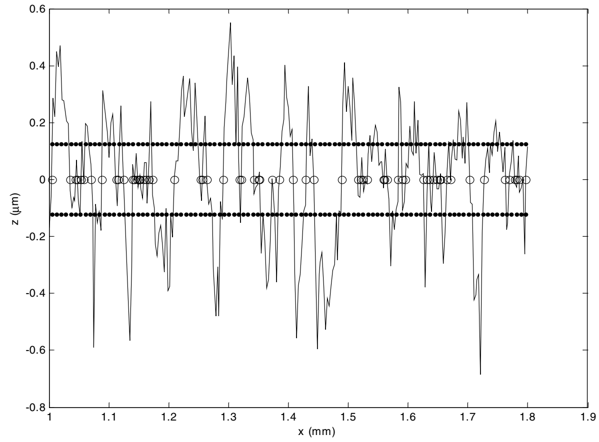

Figure 5. Part of a roughness profile with a sampling length 0.8 mm, together with its complete set of zero crossing points (small circles). The two sets of 'discs' indicate the thresholds for discrimination.

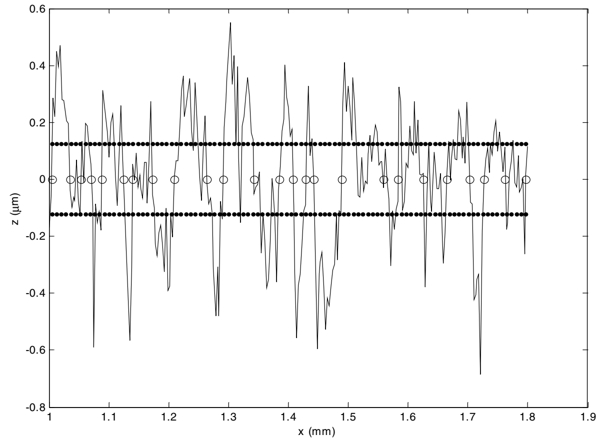

Figure 6. The reduced set of zero crossing points used to define the roughness profile elements. Here, c_k and c_{k+1} are replaced by c_k when the part of the profile between them fails the discrimination tests.

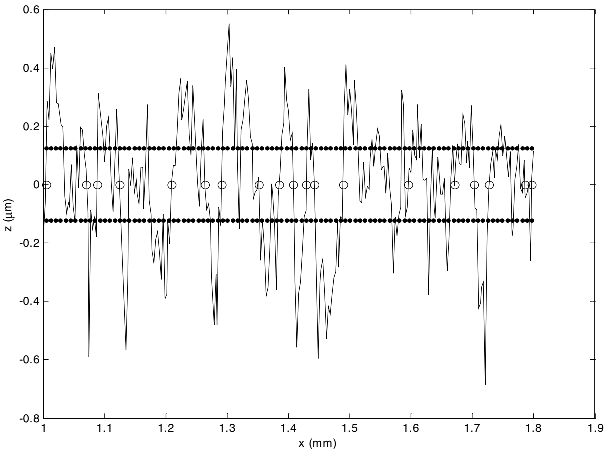

Figure 7. The reduced set of zero crossing points used to define the roughness profile elements. Here, c_k and c_{k+1} are replaced by c_{k+1} when the part of the profile between them fails the discrimination tests.

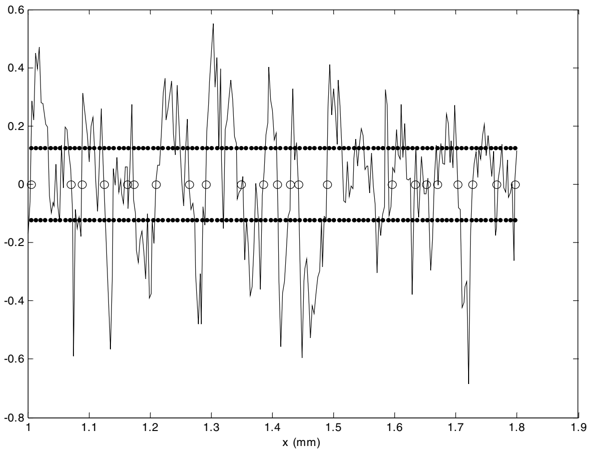

Figure 8. The reduced set of zero crossing points used to define the roughness profile elements. Here, c_k and c_{k+1} are replaced by $(c_k + c_{k+1})/2$ when the part of the profile between them fails the discrimination tests.

the three implementations (A, B and C) of step 2. The table also shows (in rows 5, 6 and 7) the calculated values for the same five sampling lengths after reversing the order of the points in the measurement data set, i.e., simulating a measurement of the data in the reverse direction.

In figure 5, a part of the roughness profile (data set 1 in table 1) corresponding to a sampling length of 0.8 mm is presented, together with its complete set of zero crossing points. Figures 6–8 show the (reduced) set of zero crossing points used to define the roughness profile elements, and the effect of implementing step 2 of the algorithm in different ways: c_k and c_{k+1} are replaced, where necessary, by (A) c_k (figure 6), or (B) c_{k+1} (figure 7), or (C) the mean of c_k and c_{k+1} (figure 8). Details from figures 6–8 showing the positions of the reduced set of crossing points between $x = 1.0$ mm and $x = 1.2$ mm for the three algorithms, respectively, are illustrated in figure 9.

7. Discussion of the results

The results given in table 1 indicate that there is a considerable amount of variation in the (mean) value of RSm arising from the different implementations (A, B and C) of step 2 of the

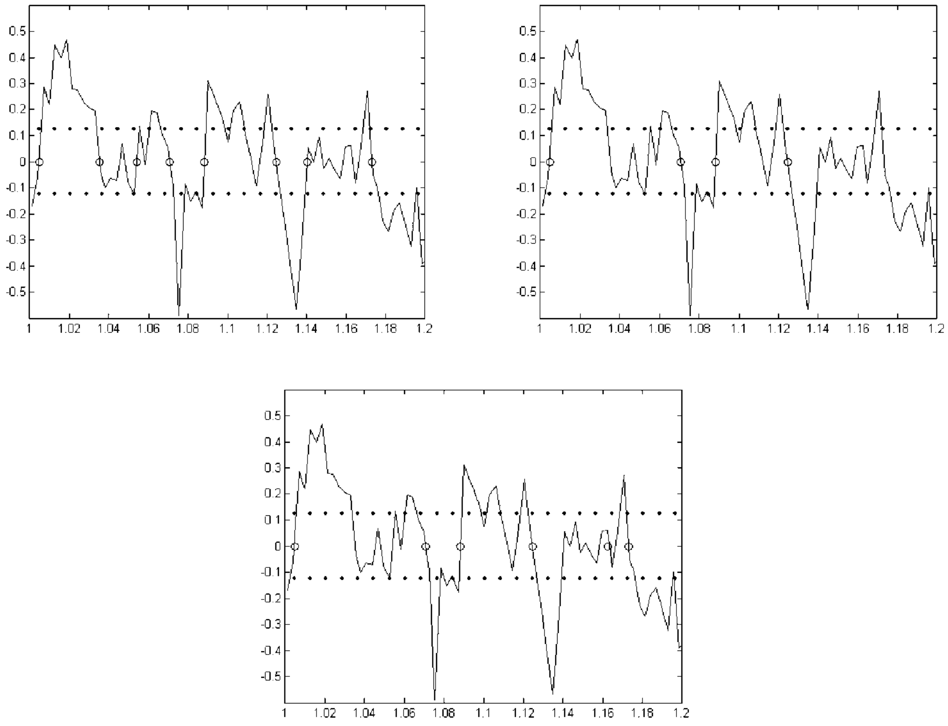

Figure 9. Details from figures 6–8 showing the positions of the reduced set of crossing points between $x = 1.0$ and 1.2 mm for the three algorithms, respectively.

proposed algorithm. For example, the results obtained from implementations A and B differ from that obtained from implementation C by as much as 12% (of the value returned by implementation C). In addition, there is a considerable amount of variation in the value of RSm for *individual* data sets. This is caused predominantly by the three implementations identifying different numbers N of profile elements within the sampling length, with differences in the length d of the interval spanned by the profile elements having a lesser affect. It can be expected that other interpretations of the definition of the RSm parameter might lead to algorithms that produce results that differ by at least as much as is observed here.

The results also indicate that the calculation of this particular parameter can vary considerably for different data sets measured on the same surface, both in terms of their position on the surface as well as the direction of measurement. For example, for all three implementations, data set 3 gives a consistently high value for RSm. Furthermore, for implementation C, data set 5 gives a value for RSm that varies considerably depending on the direction of measurement.

Without an uncertainty statement to accompany the RSm values given here it is difficult to *quantify* the significance of the differences in the results. However, it is noted that the variation in RSm estimated due to algorithm implementation is of the same order as that due to sample. It is suggested that the difference in the values is large enough to question the completeness of the definition of this parameter, as well as its usefulness as a measure of the functionality of general surfaces.

8. Summary

This paper has been concerned with ambiguities in the definitions of surface-texture parameters, particularly with regard to the calculation of the spacing parameter RSm from its definition given in ISO 4287 (1997). A specification of an algorithm for calculating RSm, subject to a number of technical variations, has been given, and the results obtained by applying the algorithm, with its variations, to simulated and real measurement data sets have been presented. Although the variations are seemingly minor details, and the algorithm with each variation is consistent with the definition of the RSm parameter, appreciable differences in the values of RSm have been obtained. Consequently, there are implications for traceability of surface-texture measurement, and the role of the RSm parameter as currently defined for conveying useful functional information about a surface. Although the focus of this paper has been on the RSm parameter, it is expected that similar problems may arise for other surface-texture parameters.

Acknowledgments

The work was funded by the UK National Measurement System Policy Unit Programme for Length 1999–2002 under Project 5.3, milestone 5.3.2. The authors thank Graham Peggs, Maurice Cox and Alistair Forbes for their valuable comments.

References

Hume K J 1980 *A History of Engineering Metrology* (London: Mechanical Engineering Publications Ltd) ch 8

ISO 3274 1996 *Geometrical product specifications (GPS)—Surface Texture: Profile Method—Nominal Characteristics of Contact (stylus) Instruments* (International Organization for Standardization)

ISO 4287 1997 *Geometrical Product Specifications (GPS)—Surface Texture: Profile Method—Terms, Definitions and Surface Texture Parameters* (International Organization for Standardization)

ISO 4288 1996 *Geometrical Product Specifications (GPS)—Surface Texture: Profile Method—Rules and Procedures for the Assessment of Surface Texture* (International Organization for Standardization)

ISO 11562 1996 *Geometrical Product Specification (GPS)—Surface Texture: Profile Method— Metrological Characteristics of Phase Correct Filters* (International Organization for Standardization)

Leach R K 2001 *Measurement of Surface Texture Using a Stylus Instrument. Measurement Good Practice Guide No 37* (National Physical Laboratory)

Stout K J and Blunt L A 2000 *Three-dimensional Surface Topography* 2nd edn (London: Penton Press)

SURFSTAND 2001 The development of a basis for 3D surface roughness standards *Final Report* SMT-CT98-2209

Whitehouse D J 1982 The parameter rash—is there a cure? *Wear* **83** 75–8