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MODIFICATION OF ROBUST FILTERING OF STRATIFIED SURFACE TOPOGRAPHY

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Abstract

Various components of surface texture are identified, namely form, waviness and roughness. Separation of these components is done by digital filtering. Several problems exist during analysis of two-process surfaces. Therefore the Gaussian robust profile filtering technique was established and has been studied here. The computer generated 2D profiles and 3D surface topographies having triangular scratches as well as measured stratified surfaces were subjected to filtration. However even robust filter applications cause distortion of profiles having valleys wider than 100 µm. In order to minimize the distortion associated with wide and deep valleys, the robust filter should be modified. A special procedure was elaborated for minimizing distortion of roughness profiles caused by filtration. Application of this method to analyses of several profiles was presented. The difference between 1-D and 2-D filtering of surface topography using the same kind of filter was discussed. As a result we found that modification of a 2-D surface topography filter was not necessary.

Keywords: two-process surfaces, digital filtering, robust filter, valley suppression filter, modification of filter.

1. Introduction

A necessary preliminary step to numerical assessment of surface profiles is to extract the frequency components representative of the roughness and to remove those that would be irrelevant. Digital filtering is used for this purpose. Recently, the Gaussian filtering technique was adapted to filtration of surface profiles [1]. The Gaussian filtering technique solved the problems of phase distortion. However the edge problem must be dealt with (marginal – running-in and running-out lengths), where roughness and waviness cannot be calculated unambiguously. In order to overcome this problem, a robust Gaussian regression filter that works without running-in and running-out lengths was developed [2, 3].

The performance of the Gaussian filtering technique is affected by certain conditions, especially for surfaces having freak signals (outliers) such as grooves, scratches and scores. Multi-process textures, like plateau honed cylinder surfaces are examples of such topographies. Although the fine texture marks fall well within the accepted bandwidth for the sample length (“cut-off”), the scratches do not. They are too wide. For these surfaces, the distortion after Gaussian filtering can be also great [4]. One possibility to overcome this problem is to increase the cut-off from 0.8 mm to 2.5 mm [5]. Another possibility is the development of other types of filters.

For the above reasons, the Rk filtering technique [6] using two-step Gaussian filtering is recommended by ISO (ISO 13565-1). However it cannot always restrict the influence of freak

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characteristics (particularly for profiles with high and wide peaks, see Fig. 1). In addition, the edge problems still exist.

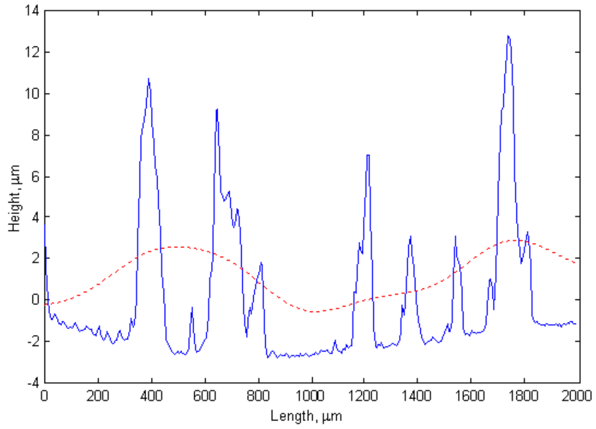

Fig. 1. Unfiltered profile (thick line) and waviness profiles after using the Rk filter (dashed line).

Consequently, the Gaussian robust profile filtering technique was established [2, 3]. It is important that the robust filters behave neutrally for surfaces of normal ordinate distribution. The robust Gaussian filtering technique proposed in [2, 3] used the Tukey weight function to perform the robust filtering. Other robust weight functions [7] were compared in [8]. A novel Gaussian filtering algorithm (ADRF) was proposed and analyzed with computer simulation of a case study. Proposals of robust filters for surface topography assessment were given in [9–11].

Generally robust filtering methods that assure similar results to Gaussian regression filtration of surfaces of normal ordinate distribution caused large distortion of roughness profiles of stratified surfaces. So the selection of the filter type should be a compromise. The Tukey method showed good performance for stratified and Gaussian profiles. However computation time is long. The other proposed functions are Hampel and Andrews. The ADRF function caused big distortion of surfaces having deep valleys of large width. Short computation time is its advantage. Median absolute deviation MAD is a more robust scale parameter than median absolute MED [12, 13]. However, even robust filters with a cut-off of 0.8 mm caused distortion of profiles with valleys wider than 100 µm.

A procedure using the envelope method [14–16] is another possibility. The upper envelope of a profile traced by a particular structural element is obtained by placing an infinite number of identical structural elements in contact with the profile and taking the lower boundary of all these structural elements. Usually during profile analysis, circles and horizontal segments are used as structural elements. When a circle is applied, a radius of 25 mm has been shown to correspond to a cut-off of 0.8 mm [14]. Whitehouse and Torrance found that this method is good for the analysis of multi-process texture [15, 16]. The MOTIF (ISO 12085) method is based on the envelope system and is suitable as an alternative approach to the mean line system [17, 18].

Recently, morphological filters were developed for scientific use. There are two basic types of these filters, namely the closing filter and the opening filter. These filter kinds are based on erosion and dilation procedures. Morphological filters are considered by ISO (ISO-DTR 16610-1). They were described in [19, 20].

An interesting attempt to use the wavelet transform to separate features of different scales relevant to the manufacturing process and functions was presented in paper [21]. Filtering by wavelet transform of three-dimensional surfaces can be found in [22, 23].

The fundamental aim of the current research is to develop a procedure for robust filtering of a surface topography with wide and deep valleys. Modification of an existing robust filter in order to avoid distortion of such surface roughness is the real contribution of this paper. Both measured and computer-generated surfaces are the objects of the investigations.

2. Filtration procedures

The transmission properties of the ISO 11562 Gaussian filter are determined by its weighting function. A filter mean line $w(x)$, which emerges from the convolution of measured profile $z(x)$ with the weighting function $s(x)$ is the result of filtering [2]. The convolution integral is given by:

$$w(x) = \int_{x_1}^{x_2} z(x-\xi)s(\xi)d\xi \tag{1}$$

or:

$$w(x) = \int_{x_1}^{x_2} s(x-\xi)z(\xi)d\xi\,. \tag{2}$$

The original measured profile $z(x)$ can be divided into low-frequency waviness $w(x)$ and high-frequency roughness $r(x)$: $r(x) = z(x) - w(x)$.

In order to analyze the entire assessment length, a Gaussian regression filter (GR) was developed. The filter mean line function $w(x)$ of the filtered profile minimizes the squared deviations of the measured profile $z(x-\xi)$ weighted by a function $s(\xi)$ and integrated over the interval $0<(x-\xi)< L$, where L is the assessment length. The following formula is used for calculation of the filter mean line [2, 3]:

$$w(x) = \int_{x_1}^{x_2} z(x-\xi)s_0(\xi)d\xi \tag{3}$$

with:

$$s_0(\xi) = s(\xi) / \int_{x_1}^{x_2} s(\xi)d\xi\,. \tag{4}$$

The weighting function is scaled so its total area always takes the value of unity.

The robust filter is a modification of the Gaussian regression filter; it uses additional weights:

$$w(x) = \int_{-\infty}^{\infty} z(x-\xi)\cdot \rho(x-\xi)s(\xi)\cdot d\xi\,. \tag{5}$$

The additional weight $\rho(x)$ decreases in the places of valleys or peaks [2, 3]. The iterative procedure is used. In the first iteration step the additional weight takes the value of unity. So the roughness and waviness profiles are calculated in the previously discussed way (Gaussian regression filtering).

Various weight functions were compared, for example Tukey:

$$\rho(x) = \begin{cases} \left(1-v^2\right)^2, & |v| \le 1 \\ 0, & |v| > 1 \end{cases} \tag{6}$$

where: $v = r(x)/(cm)$

The Tukey weight function was adopted with c = 4.4 [12, 13].

Hampel:

$$\rho(x)=\begin{cases}1, & |v|\le a\\ a/|v|, & \mathrm{a}<|v|\le b\\ a\dfrac{c-|v|}{(c-b)|v|}, & \mathrm{b}<|v|\le c\\ 0, & |v|>c\end{cases} \tag{7}$$

where: $v = r(x)/m$, $0 < a < b < c < \infty$, a = 1, b = 1.5, c= 3 [12, 13].

Andrews:

$$\rho(x)=\begin{cases}\dfrac{1}{\pi v}\sin(\pi v), & |v|\le 1\\ 0, & |v|>1\end{cases} \tag{8}$$

$$v = r(x)/(cm),$$

where the regression coefficient c was 1.5π [12, 13].

The scale parameter m was equal to MED or MAD.

$$MED = median|r| \tag{9}$$

$$MAD = median|r - med(r)| \tag{10}$$

During filtering, an iterative procedure was used. The calculation was done, until $(\Delta m)/m$ was <0.001, where: $\Delta m = m[i] - m[i-1]$.

The valley suppression Rk filter was also taken into consideration. It was based on a Gaussian regression filter of profile. An upper envelope filter was used too, when wheel was used as the structuring element. The calculation was done using the method described in [24]. In profile analysis, only the Tukey filter was used. During these investigations the cut-off was 0.8 mm, the assessment length was 4 mm and the sampling interval was 1 μm. No short wavelength filter was used. The other described filters were applied in 3D surface topography study. The presented robust filters for the analysis of 2D surface profiles were extended into the analysis of 3D surface topographies [2, 3]. The weight functions presented above were used. Valley suppression (Rk) procedures as well as upper envelope filters were developed in order to study 3D surface topography filtering. In calculations the same cut-off was used as that during 2D profiles filtration. The radius of the structuring element was 25 mm.

3. Results and analysis

3.1. Filtering of 2D profiles

It was found that even robust filters caused distortion of profiles having a wider valley than 100 μm [12, 13]. These valleys can exist on cylinder surfaces (for example in the circumferential direction). In order to minimize wide valley distortion, a special procedure was developed. The filtering modification should take place only for profiles having deep valleys (of negative skewness). For other profiles the filter should work without modification. The first filtering step was to use a Gaussian regression filter. The new procedure was used when the *Rsk* parameter was smaller than –1.5. Next, the special method of deep and wide valley identification was applied. The valley was identified as deep and wide when the successive ordinates were smaller than the median value of all the profile ordinates in the distance of 125 μm. The valley identification happened only once (after Gaussian regression filter application and skewness check). In this location the additional weight $\rho(x)$ became smaller than for unmodified robust filter application, therefore the modified filter behavior was neutral. Because the use of a Gaussian regression filter caused the existence of additional overshoot in the valley neighborhood, the weight became smaller in the overshoot place on a length depending on the cut-off. When the Tukey filter was used in the place of a wide and deep valley and close to it when $\rho(x) < 0.8$, then $\rho(x) = 0$. During filtering, an iterative procedure was used, as in the application of the unmodified robust filter. In each iteration step the weight was calculated and diminished when the given condition was fulfilled. The iteration was carried out until the change of the scale parameter between two iteration steps lay within a tolerance limit (<0.001). In our research mainly the Tukey filter ($c = 4.4$) was modified, but the other robust filter can be changed in this way.

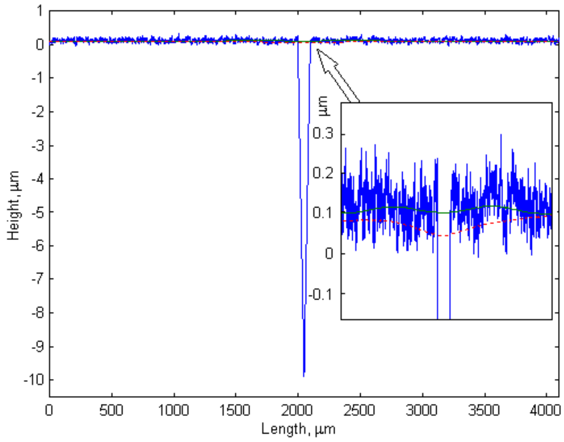

Fig. 2. Unfiltered profile (thick line) and waviness profiles after using a robust filter (dashed line) and a modified robust filter (thin line).

Figures 2 and 3 present unfiltered simulated profiles each having deep a valley of 100 µm and 200 µm width, and of 10 µm and 20 µm depth, respectively and waviness profiles after using a Tukey filter (MAD was the scale parameter) and the modified filter.

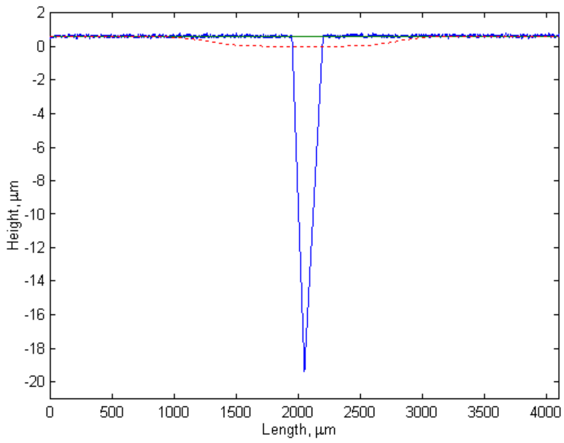

Fig. 3. Unfiltered profile (thick line) and waviness profiles after using a robust filter (dashed line) and a modified robust filter (thin line).

Tables 1 and 2 show the calculated parameters of the unfiltered and filtered profiles and roughness parameters. *Ra* is arithmetic mean deviation, *Rq* root-mean-square deviation, *Rt* total height, *Rp* maximum peak height, *Rsk* skewness, *Rku* kurtosis, *R*Δ*q* root-mean-square slope of the roughness profile and *RSm* mean width of the roughness profile elements. Because the waviness content of unfiltered profiles was small, parameters of unfiltered profiles were treated as reference data. Therefore the relative differences Δ were calculated as (*UF*–*F*)/*UF*, where *UF* were parameters of an unfiltered profile, and *F* were parameters of the filtered profile.

Table 1. Parameters of the unfiltered profile shown in Fig. 2 and roughness parameters after using a robust filter and its modified version (*M*). Δ indicates the difference with relation to the unfiltered profile.

	Ra, µm	*Rq*, µm	*Rt*, µm	*Rp*/*Rt*	*Rsk*	*Rku*	*RSm*, µm	*R*Δ*q*
Unfiltered profile	0.2383	0.8951	10.194	0.0311	–8.1001	71.5621	204.800	0.0442
Tukey 4.4 *M*	0.2381	0.8946	10.195	0.0316	–8.1013	71.5818	204.800	0.0442
Δ (Tukey 4.4 *M)*	0.084%	0.056%	–0.01%	–1.61%	–0.02%	–0.03%	0	0
Tukey 4.4	0.2363	0.8895	10.153	0.0313	–8.1162	71.8515	195.048	0.0441
Δ (Tukey 4.4)	0.839%	0.626%	0.402%	–0.64%	–0.2%	–0.4%	4.762%	0.226%

Table 2. Parameters of the unfiltered profile shown in Fig. 3 and roughness parameters after using a robust filter and its modified version (*M*). Δ indicates the difference with relation to the unfiltered profile.

	Ra, µm	*Rq*, µm	*Rt*, µm	*Rp*/*Rt*	*Rsk*	*Rku*	*RSm*, µm	*R*Δ*q*
Unfiltered profile	1.1471	2.7867	20.186	0.0396	–4.9718	27.7317	4096.0	0.0508
Tukey 4.4 *M*	1.1467	2.7858	20.186	0.0398	–4.9723	27.7367	4096.0	0.0508
Δ (Tukey 4.4 *M)*	0.035%	0.032%	0	–0.51%	–0.01%	–0.02%	0	0
Tukey 4.4	1.1030	2.7151	20.15	0.0564	–4.9658	27.9088	4096.0	0.0507
Δ (Tukey 4.4)	3.845%	2.569%	0.178%	–42.4%	0.121%	–0.64%	0	0.197%

It is evident from the analysis of Table 1 that only the error of *Rp*/*Rt* increased after using the modified method of filtration; the errors of the other parameters decreased, for example for *RSm* from 4.76% to 0. We found from the analysis of Table 2 that all the roughness parameters improved after using the modified procedure except for *RSm* which had no errors to begin with. The decreases of some deviations were great. The absolute values of the largest errors resulting from the modified procedure were 0.51%. One should note that an improved filter operates differently than the unmodified robust filter only on valleys of large width (not on peaks and not wide valleys). Differences between the behavior of the Tukey filter and its modified version were found only for valleys of large width (valley in Fig. 4). These differences found for valleys of small width and peaks were negligible (see Fig. 5).

Other profiles having a lot of valleys were analyzed. It was confirmed that the behavior of the modified filter was better in comparison with the unmodified robust filter. Improvement in the majority of the calculated roughness parameters was great when valleys of large width were present in a profile (see Fig. 3 and 4).

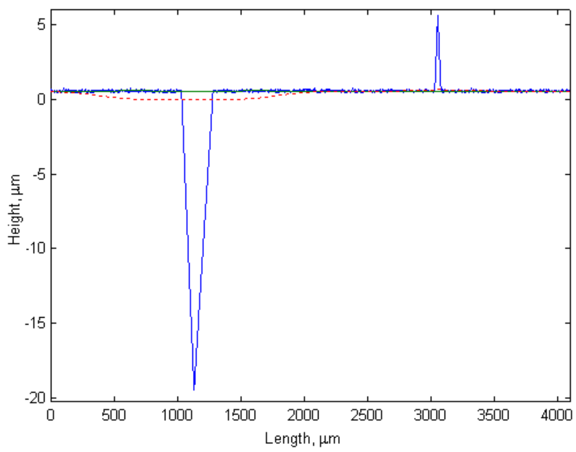

Fig. 4. Unfiltered profile (thick line) and waviness profiles after using a robust filter (dashed line) and a modified robust filter (thin line).

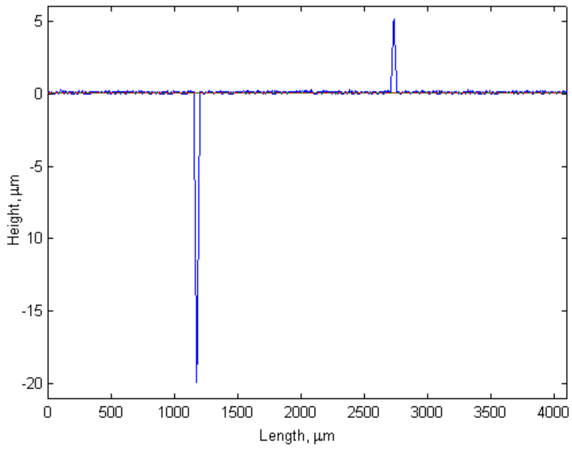

Fig. 5. Unfiltered profile (thick line) and waviness profiles after using a robust filter (dashed line) and a modified robust filter (thin line).

Plateau honed cylinder profiles were also studied. Fig. 6 and 7 show examples of waviness profiles after using a Tukey filter and its modified version. Tables 3 and 4 present roughness parameters of profiles shown in Fig. 6 and 7, respectively.

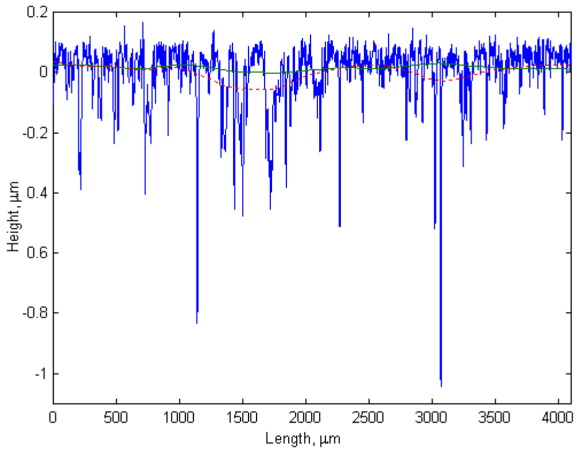

Fig. 6. Unfiltered cylinder profile (thick line) and waviness profiles after a using robust filter (dashed line) and a modified robust filter (thin line).

The use of the modified filter caused smaller differences than the unmodified robust filter with respect to the unfiltered profile shown in Fig. 6 for a majority of the analyzed roughness parameters (including the amplitude parameter and *Rp*/*Rt*).

Table 3. Parameters of the unfiltered cylinder profile shown in Fig. 6 and roughness parameters after using a robust filter and its modified version (*M*). Δ indicates the difference with relation to the unfiltered profile.

	Ra, µm	*Rq*, µm	*Rt*, µm	*Rp*/*Rt*	*Rsk*	*Rku*	*RSm*, µm	*R*Δ*q*
Unfiltered profile	0.0712	0.1102	1.231	0.1464	–3.3414	21.7497	36.2478	0.0269
Tukey 4.4 *M*	0.0696	0.1091	1.247	0.1461	–3.4658	23.3534	35.9298	0.0268
Δ (Tukey 4.4 *M)*	2.247%	0.998%	–1.3%	0.205%	–3.72%	–7.37%	0.877%	0.372%
Tukey 4.4	0.0696	0.1085	1.21	0.1404	–3.4549	22.7178	35.6174	0.0269
Δ (Tukey 4.4)	2.247%	1.543%	1.706%	4.098%	–3.4%	–4.45%	1.73%	0

The profile shown in Fig. 7 had valleys of greater width than the profile shown in Fig. 6.

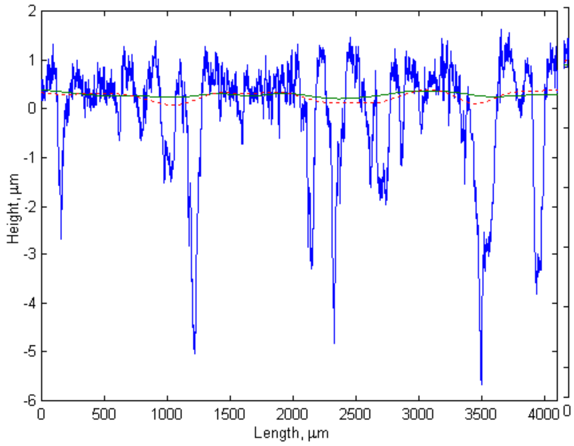

Fig. 7. Unfiltered cylinder profile (thick line) and waviness profiles after using a robust filter (dashed line) and a modified robust filter (thin line).

The application of the modified filter caused smaller errors than the unmodified filter for all the analyzed roughness parameters. The relative errors of the parameters were usually smaller than 0.7% and diminished from 4.3% (*Ra*) or 3.83% (*Rp*/*Rt*). Only the *RSm* parameter error was 3.7%, but it decreased from the value of 10.64% (see Table 4).

Table 4. Parameters of the unfiltered cylinder profile shown in Fig. 7 and roughness parameters after using a robust filter and its modified version (*M*). Δ indicates the difference with relation to the unfiltered profile.

	Ra, µm	*Rq*, µm	*Rt*, µm	*Rp*/*Rt*	*Rsk*	*Rku*	*RSm*, µm	*R*Δ*q*
Unfiltered profile	0.75	1.0851	7.3001	0.2231	–2.0888	7.7527	59.5238	7.5034
Tukey 4.4 M	0.745	1.0796	7.309	0.2245	–2.0906	7.7818	61.7284	7.5025
Δ (Tukey 4.4 M)	0.66%	0.502%	–0.12%	–0.66%	–0.08%	–0.38%	–3.7%	0.012%
Tukey 4.4	0.7177	1.0526	7.1560	0.2316	–2.0988	7.9445	53.1915	7.5336
Δ (Tukey 4.4)	4.298%	2.997%	1.974%	–3.83%	–0.48%	–2.47%	10.638%	–0.4%

Modification of robust filters in the deep and wide valley neighborhoods (where overshoots take place) is very important. Fig. 8a and 8b shows unfiltered profiles presented in Fig. 6 and 7, respectively, as well as waviness profiles after using modified versions of the Tukey filter without (dashed line) and with additional decreasing weight $\rho(x)$ in places of valley neighborhoods (thin line). Differences between waviness profiles shown in Fig. 8a are small. However, lack of modification of robust filter near wide valleys causes distortion of the roughness profile (see Fig. 8b).

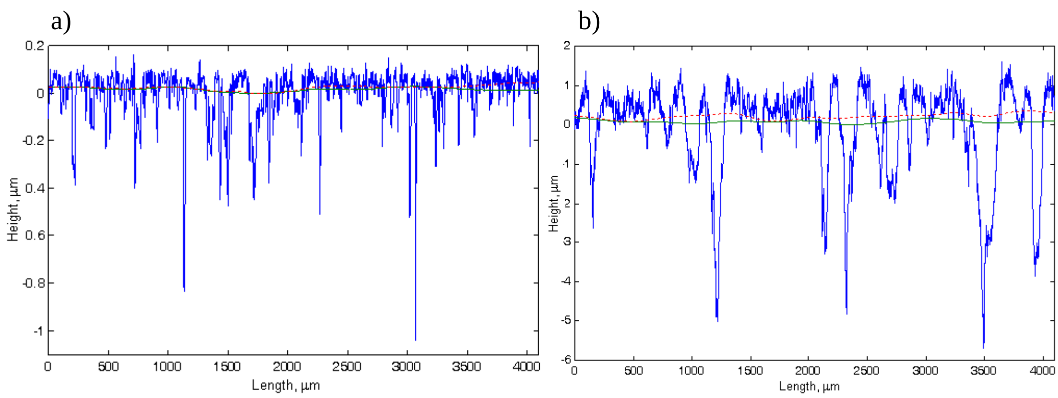

Fig. 8. Unfiltered profile (thick lines) and waviness profiles after using a modified robust filter (thin lines) and a modified robust filter without modification in the deep and wide valleys neighbourhoods (dashed lines).

We obtained similar results after study of other cylinder profiles. After using the modified procedure, the majority of the parameter errors decreased. The modified procedure caused the improvement in the determination of amplitude roughness parameters and parameters describing the shape of the roughness profile ordinate distribution like *Rp*/*Rt* and *Rsk*. The shapes of waviness profiles were improved too in comparison with the results of the robust filter. The new filter reacted correctly in existence of wide valleys, but its behavior was similar to that of the robust filter for narrow valleys on surfaces. Information that time to compute the filtered profile image was similar to that during the use of usual robust filtering is also important.

The modification of robust filtering can be applied not only to plateau honed cylinder surfaces. Many profiles with oil pockets created by the burnishing (embossing) technique were analyzed. It was found that application of a modified filter causes better transformation of such profiles. Fig. 9 presents the example of waviness profiles after using a Tukey filter and its modified version.

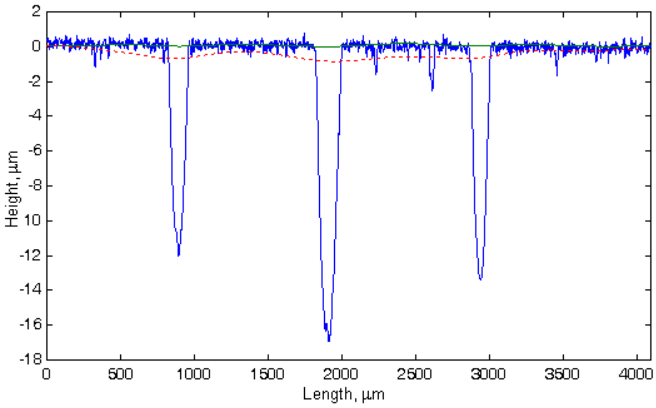

Fig. 9. Unfiltered profile (thick line) with burnished oil pockets and waviness profiles after using a robust filter (dashed line) and a modified robust filter (thin line).

3.2. Filtering of 3D surface topography

One can note that the distortion of 3D surface roughness measurement result by a 2-D filter should be not greater than distortion of 2D roughness profiles by a 1-D profile filter of the same type. The change is the same for one-directional surfaces, when the valleys are perpendicular to the measurement direction. For valleys inclined to the measurement direction, the distortion of the surface by a 2-D filter should be smaller, because for a 3D surface and a 2-D filter, the valley of its real width is subjected to filtration, however for a 2D surface and a 1-D filter, not the real valley but a projection of the valley in the measurement direction (of greater width) is filtered. In Fig. 10 the real valley width is d, but the width of the projection of the valley on the x direction is $d/(\sin\beta)$.

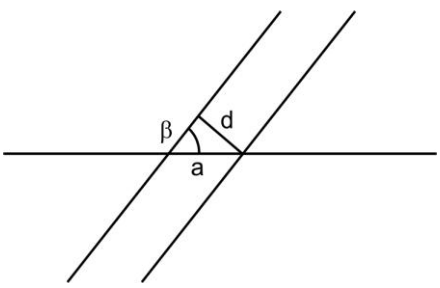

Fig. 10. Width of triangular valley.

The existence of valleys of different width and different angular position (β angle – see Fig. 10) to the measuring axis *x* was simulated. These valleys were inclined to the *x* axis (horizontal). Values of β angle amounted to 90, 30 and 15 degrees (see Table 5). Only when the angle β was equal to 90 degrees, was the 3D surface topography valley width equal to the 2D profile valley width. In other cases the real width was smaller than its projection on the *x* (lateral) axis. We analyzed the effect of the type of filter and angular orientation of the triangular valley of the same real width on the overshoot described by the $SRp(f)/Sz(n)$ parameter, where $SRp(f)$ was the maximum summit height of the high-pass filtered surface, and $Sz(n)$ was the maximum height of the unfiltered surface topography.

Table 5. The effect of the type of filter and angular width location on surface roughness distortion, characterized by $SRp(f)/Sz(n)$ parameter.

Kind of filter \ β, °	90	30	15
GR	0.1033	0.1051	0.1003
Rk	0.0359	0.0358	0.0335
Tukey (4.4)	0.0315	0.0316	0.0315
Hampel (1.0; 1.5; 3.0)	0.0319	0.0318	0.0316
Envelope filter	0.0202	0.0202	0.0202
Andrews (1.5)	0.0328	0.0314	0.0316

The real valley width was 80 μm. The projection of valley width in the *x* direction was 80 μm for a β angle of 90°, 309 μm for 15°, and 160 μm for 30°. It can be seen from Table 5 (and similar analysis concerning other valley widths) that the effect of the filter depends only on the real valley width, not on its projection on the *x* axis. Therefore for smaller β angle than 90°, the profile distortion by a 1-D filter is greater than the distortion of 3D surface topography distortion by a 2-D filter. A similar conclusion was obtained in [4].

Figure 11 presents surfaces with a triangular scratch of width 80 μm, inclined to the measurement direction (*x* axis) by an angle of 15°(a) and 30°(b).

Because honing valleys are not perpendicular to the measurement direction, distortion of plateau honed cylinder surface topography roughness caused by 2-D filtering should then be smaller than that of 2D cylinder profiles. So modification of a robust digital filter in order to 3D surface topography filtering in the authors' opinion is not necessary.

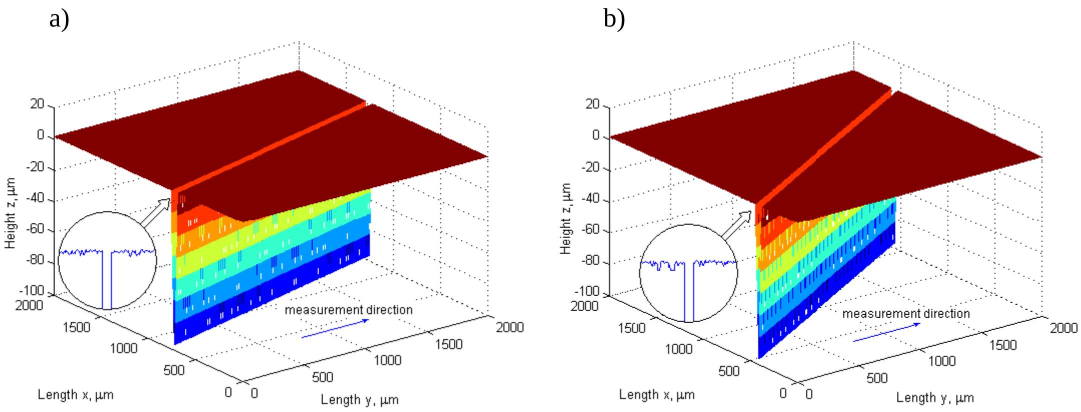

Fig. 11. Views of surfaces having a triangular valley inclined to measurement direction by an angle of 15° (a) and 30° (b).

4. Conclusions

Even robust filter application causes distortion of roughness profiles having wider valleys than 100 µm for a filter cut-off of 800 µm. In order to minimize distortion of wide and deep valleys, the robust filter should be modified. The special procedure was then elaborated.

The first filtering step was to use a Gaussian regression filter. The new procedure was used only when the *Rsk* parameter was more negative than (–1.5). Then the valley was identified when the successive ordinates were smaller than the median value of all the profile ordinates at the distance of 125 μm. In this location the additional weight $\rho(x)$ became smaller than for unmodified robust filter application. The weight became also smaller near to identified wide valleys. The modified procedure caused the improvement of calculations of the majority of roughness parameters. The modified filter operates differently than the unmodified robust filter only on valleys of large width (not on peaks and not wide valleys).

Distortion of a 3D surface by the 2-D filter should not be bigger than the distortion of 2D profiles by the same 1-D filter type, because on 3D surfaces a valley of its real width is subjected to 2-D filtration, however in the 2D profile case, the projection (of not smaller width) of the valley on the measurement direction is filtered by a 1-D profile filter. So the modification of the 2-D surface topography filter in our opinion is not necessary.

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