Morphological filtration of two-process profiles

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Abstract. Applications of morphological filters for two-process profiles were analysed. Dilation, closing and alternating sequential (closing + opening) filters were used with a circle (disk) as a structuring element. An original method of a disk radius selection was elaborated for two-process profiles. This procedure was applied for many simulated and measured profiles. Behaviors of morphological filters were compared with those of double Gaussian (Rk) filter. Robust filter was also taken into consideration. In calculation, TalyMap software was used. The proposed procedure was found to be very useful. It was developed for 2D profiles but it can be easily extended for an areal (3D) surface topography filtering. From among morphological filters, the alternate sequential filter is suggested.

Key words: morphological filtration, surface topography, stratified textures.

1. Introduction

Filtration techniques are widely used as the pre-processing tools to remove unwanted components of surface texture. The roughness profile is derived from the primary profile by retaining the short-wave component. The unwanted elements of the surface texture, being long wavelengths, are commonly referred to the waviness, affecting negatively functional performance of machine elements. An increase in the waviness on the inner and outer raceways causes an increase in the vibration level of bearings [1, 2]. The parameters calculated from the unfiltered (raw) profile are called P-parameters, from the roughness profile – R-parameters, while from the waviness profile – W-parameters.

Mean-line based filters are commonly used for separation of different components of surface texture. Morphological filters, being their complement are believed to give better results for stratified surface topographies. They have found many applications in practice. A direct algorithm of a traditional envelope filter was developed by Shunmugam and Radhakrishman [3]. Morphological filters are constructed using structural elements. Usually the circular discs and horizontal lines are considered for 2D profiles while sphere and horizontal plane for areal (3D) surface topographies. The two basic morphological operations are dilation and erosion. During a dilation, the structuring element is in contact with and above the surface, but during an erosion, the structuring element is in contact with and below the texture. The closing filter is the result of a dilation followed by an erosion. The closing filter defines the upper envelope of the surface, although the traditional envelope filter was equivalent to the dilation operation [4]. The opening filter is the result of an erosion followed by a dilation, this filter defines the lower envelope. It is possible to apply a closing filter followed by an opening filter, or in the reverse way, an opening filter followed by a closing filter; these filters are called alternating sequential filters. Morphological filters are believed to offer more possibilities than traditional mean-line filters, such as multi-scale analysis [4], eliminating high peaks or valleys, reconstructing mechanical surface after stylus measurement [5] and simulating the conformable interface of two mating surfaces [6]. They can be also used in contact analysis [5]. Algorithms for morphological profile filters were presented in Reference [7].

Two-process (stratified) texture is more functionally important than one-process surface. Plateau honed cylinder surface is the typical example of two-process texture. It combines good sliding properties of a smooth surface and a great ability to maintain oil of a porous texture. It consists of smooth wear-resistant and load-bearing plateaux and deep valleys working as oil reservoirs and debris trap. Plateaued surfaces have been machined to simulate those resulting from a normal running-in process. Two-process surfaces have advantage over one-process textures [8–13]. Correct analysis of two-process texture is therefore a task of a great functional importance. Tribological properties of one-process profiles are typically characterized by the Pq parameters, being the root mean square value of the ordinates. For two-process surfaces the Ppq parameter seems to be more functionally important. It describes the root mean square value of the ordinates of the plateau (peak) profile part (ISO 13565–3).

However, there are serious problems in filtration of stratified textures using commonly used filters, such as Gaussian filter. Although the fine portion fall well within the accepted bandwidth for the cut-off, the scratches do not, because they are too

wide. The resulting roughness profile is distorted; overshoots near edges of valleys occurred. To prevent this distortion, it was recommended that the standard cut-off should be increased to 2.5 mm for this application [14]. It is necessary to use double Gaussian filter (Rk) [15] for the profile filtering. The alternative approach is to use robust Gaussian filters [16]. However applications of double Gaussian filter can also lead to distortion of roughness profiles, especially for surfaces containing wide dimples.

The authors of References [5, 17] confirmed usefulness of morphological filters for plateau-honed cylinder surface.

Filtration of simulated and measured two-process profiles using morphological filters will be studied in this work.

2. Selection of a disk radius

The present authors elaborated an original method of a disk radius selection for two-process textures. Simulated profiles contained plateaus and triangular scratches of various sizes were analysed, because they resemble two-process profiles. Measured plateau-honed cylinder profiles and profiles from other textured surfaces were also studied. Dilation, closing and alternating sequential (closing + opening) filters were used with circle (disk) being a structuring element. There is problem of determining the correct value of its radius. It is related to depth of penetration h of circle inside the valley of width a (Fig. 1).

$$h = R - \sqrt{R^2 - 0.25a^2}.$$ (1)

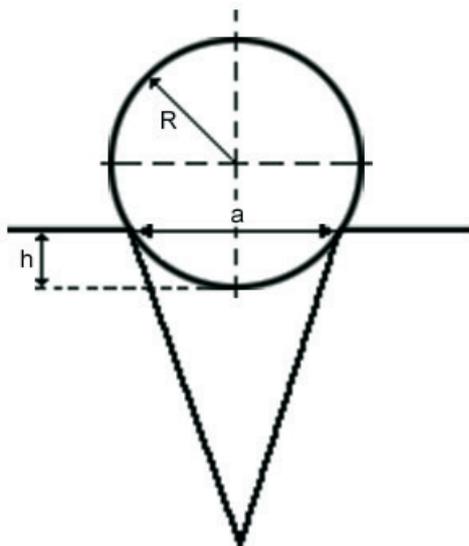Therefore the disk radius should be:

$$R = \frac{h^2 + 0.25a^2}{2h}.$$ (2)

Fig. 1. A scheme of estimation of the disk radius R of a morphological filter

The depth h should be selected properly in order to prevent distortion of the roughness profile. It was assumed that this depth should be a fraction of a waviness total height. Since waviness amplitude is typically higher for bigger texture height, the minimum depth h is larger when the Ppq parameter is higher. The ratio of the depth h to the Ppq parameter should be smaller when the Ppq parameter is higher.

Many profiles with the Ppq parameter smaller than 1 μm were analysed during selection of the minimum depth h. The following formula was used for the estimation of the h value:

$$h = -0.158Ppq^2 + 0.355Ppq.$$ (3)

The obtained ratio of depth h to the Ppq parameter is between 0.2 for comparatively rough (Ppq near 1 μm) and 0.355 for smooth plateau profile (Ppq smaller than 0.001 μm). For random profile the maximum height of the plateau portion is about 6 Ppq. Therefore the allowable depth is smaller than 0.06 of the total height of the plateau profile part.

The Ppq parameter can be easily calculated when plateau and valley parts are random (see ISO 13565–3 standard). It is the slope of a linear regression performed through the plateau region of the probability plot of a material ratio curve. There is a problem of computing this parameter for a random-deterministic texture, when valley part has a deterministic character (surfaces with isolated oil pockets is the example of those textures). However Grabon et al. presented a method of the Ppq parameter computation for textured surfaces with a deterministic pattern of valley features [18]. The Ppq parameter can be also estimated by computing the Pq parameter of profile parts free of valleys.

The proposed procedure of a disk radius selection could be easily extended to areal (3D) surface topography analysis.

3. The analysis of simulated profiles

Behaviors of morphological filters were compared with those of double Gaussian (Rk) filter [15]. A robust filter [16] was also taken into consideration. In filtrations and calculations of parameters, TalyMap software was used. Two-process profiles were simulated by adding the triangular valleys of known dimensions to modeled random one-process profiles of the given value of the Pq parameter. This parameter is equal to the Ppq parameter of two-process profile. Since plateaus of modeled profiles having triangular scratches did not contain substantial waviness, parameters of filtered and unfiltered profiles were compared.

The emptiness coefficient Pp/Pt (Pp – maximum peak height of the raw profile, Pt – total height of the raw profile) or Rp/Rt (Rp – maximum peak height of the roughness profile, Rt – total height of the roughness profile) can be used for description of the profile asymmetry. It was found that morphological filters and the Rk filter reacted differently to wide and deep valleys presence. After morphological filter usage (especially closing or dilation filters) the emptiness coefficient decreases (after the alternating sequential filter application the emptiness coefficient sometimes, for smooth plateau surface, marginally increased).

However, after double Gaussian filter application the emptiness coefficient always increased.

The differences between filters behaviours were due to the fact that morphological filters caused change of a profile details inside deep valleys, while the double Gaussian filter affected also valleys neighbouring points. This is evident in Fig. 2 presenting a simulated profile A with three valleys of width 200 µm and depth 40 µm, The Ppq parameter was 0.1 µm. Application of the traditional envelope filter (dilation) of too small disk diameter (5 mm) caused a decrease in the emptiness coefficient from 0.036 to 0.032 (Fig. 2b), but the use of the Rk filter (cut-off 0.8 mm) led to its increase to 0.11 (Fig. 2d). For profile with the wide valleys application of the double Gaussian filter caused the roughness profile distortion – overshoots appeared near the valley edges. This distortion would be higher

after the use of the Gaussian filter. After application of the dilation filter of too small disk diameter waviness contained small wavelengths (Fig. 2c).

The other important difference between morphological and Rk filters is that the morphological filters react mainly on the valley width. Because the morphological filtration is based on the geometry of both structuring element and surface to be filtered, so any spatial geometry will affect its result. It is because of the high aspect ratio around the profile valley portions, the width of valleys played the dominant role in that particular case.

Contrary, not only valley width but also depth affect behaviour of the Rk filter; roughness distortion due to improper filter application is bigger for higher valley depth. The depth of valleys of a profile B shown in Fig. 3a, of 200 µm width (the

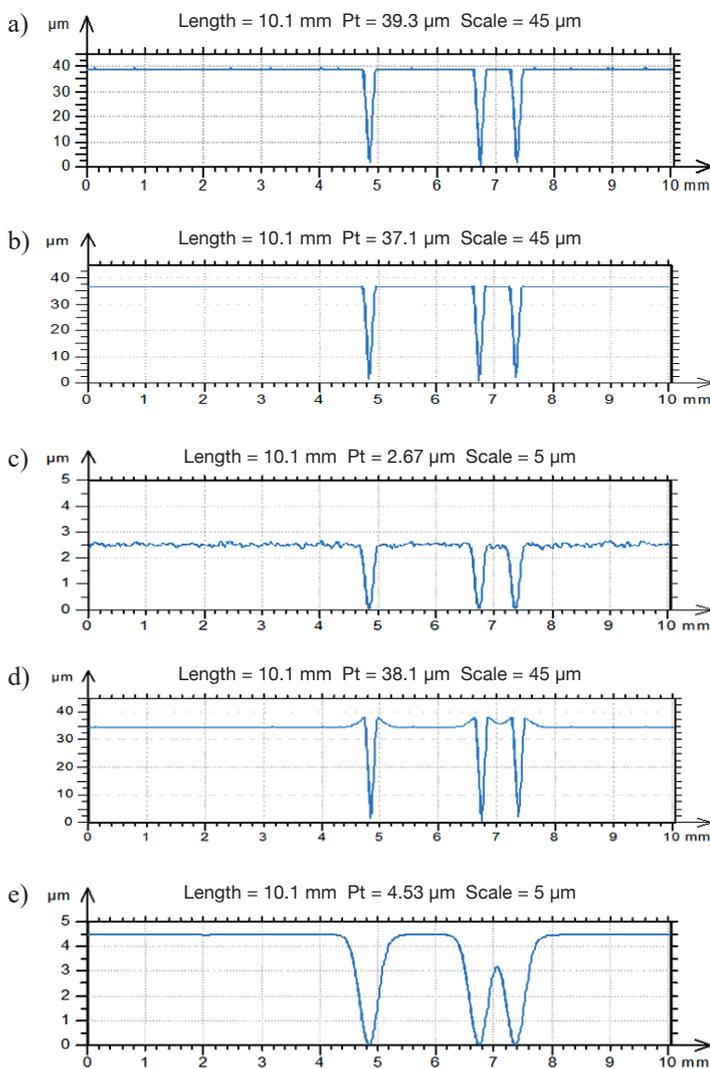

Fig. 2. Simulated unfiltered profile A – Pp = 1.41 µm (a), roughness profile filtered by the dilation filter of 5 mm disk diameter – Rp = 1.16 µm (b), waviness profile filtered by the dilation filter of 5 mm disk diameter (c), roughness profile filtered by the double Gaussian filter of 0.8 mm cut-off – Rp = 4.18 µm (d), waviness profile filtered by the double Gaussian filter of 0.8 mm cut-off (e)
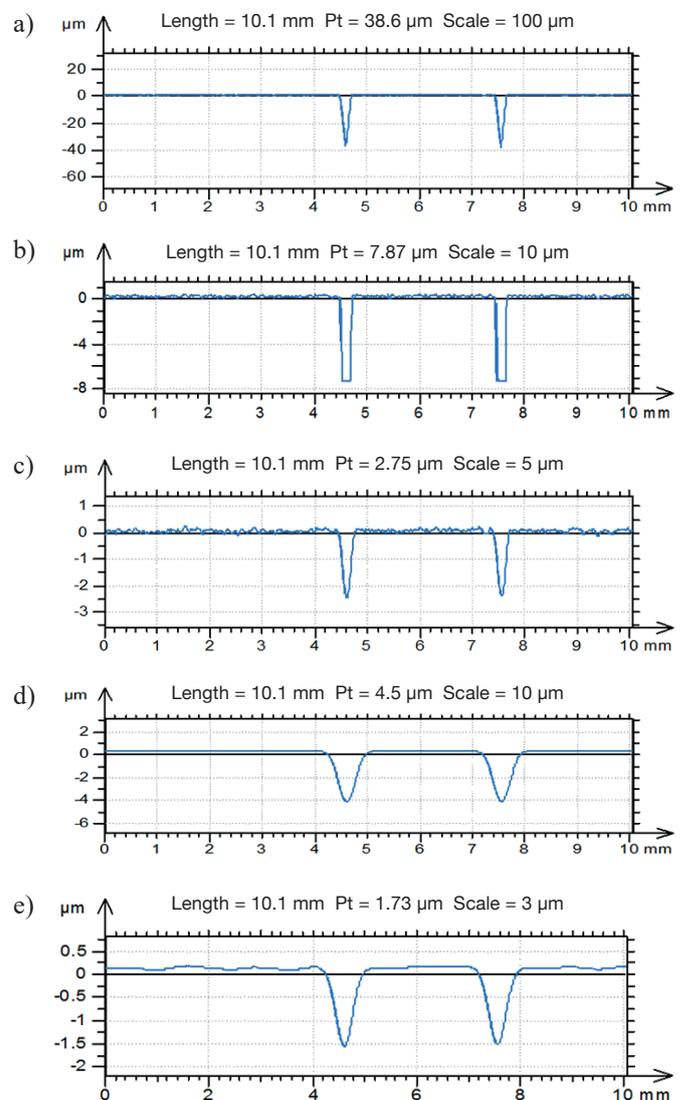
Fig. 3. Simulated unfiltered profile B (a), profile B with reduced valleys depths B1 (b), waviness profile B and B1 filtered by the dilation filter of 5 mm disk diameter (c), waviness profile B filtered by the double Gaussian filter of 0.8 mm cut-off (d), waviness profile B1 filtered by the double Gaussian filter of 0.8 mm cut-off (e)

Ppq parameter was 0.1 μm), was reduced about 5 times and profile B1, shown in Fig. 3b was obtained. However, waviness profiles after using the dilation filter of these two profiles are identical, which is shown in Fig. 3c. Contrary, the maximum height of the waviness profile filtered by Rk filter depends on the valley depth – it is about 3 times smaller after filtration of the profile with the reduced valley depth. To show changes of filtered profiles the disk of morphological filter was too small. Many simulated profiles of different standard deviations of plateaus Ppq, numbers of triangular valleys and their sizes were analysed. It was found that from among morphological filters, the alternating sequential filter application caused the smallest, but closing – the largest distortion of the roughness profile. After the closing filter application, the Rpq parameter considerably decreased and change of plateau part occurred; it is interesting that the highest points of peaks were on the same vertical level, resulting in a considerable decrease in the Rpk parameter (the reduced peak height), sometimes to 0 value, and a decrease in the Rp parameter. This behaviour can be considered as a profile distortion. Please note that the Rpk and Rpq parameters are within the requirements of the leading engine builders with regard to plateau-honed cylinder profiles, they are related to tribological properties of sliding elements like the coefficient of friction [9]. Therefore improper estimation of these parameters could lead to false prediction of functional properties of internal combustion engines. Figure 4 presents a profile C characterized by the Ppq parameter of 0.2 μm having four valleys of 100 μm widths and about 10 μm depths. This profile was filtered by the closing filter of 40 mm disk diameter, calculated according to the proposed method. It is evident from zoomed detail of the roughness profile that the highest points of all the peaks are located on the same vertical level. Consequently the Rpk parameter decreased from 0.161 μm value to 0, but the Rpq parameter decreased to 0.14 μm.

An increase in the cut-off from 0.8 mm to 2.5 mm caused a decrease of a profile distortion, when the Rk filter was used. A robust Gaussian filter reacts similarly to the Rk filter on deep valley presence. Due to the robust filter application distortions were usually small, except for the case when several deep valleys were close to each other. Figure 5 presents example of a simulated profile D.

The Ppq parameter was 0.3 μm, valleys widths and depths were about 160 μm and 20 μm, respectively. One can see that application of the sequential filter caused small change of the shape of the roughness profile. The emptiness coefficient Rp/Rt decreased from 0.059 to 0.052. However, an increase in the disk diameter from 60 mm to 125 mm (the largest possible value) did not change the emptiness coefficient. For comparatively rough plateau surface portion an application of a morphological filter with disk being a structuring element caused a decrease in the emptiness coefficient because edges of the deep valley were located under the profile highest peaks. Application of the Rk filter with 0.8 mm cut-off caused profile distortion (see Fig. 5c) and an increase in the emptiness coefficient to 0.094 value. Growth of the cut-off to 2.5 mm led to a smaller increase in the Rp/Rt ratio – to 0.065. The spacing parameter RSm (mean width of the roughness profile elements)
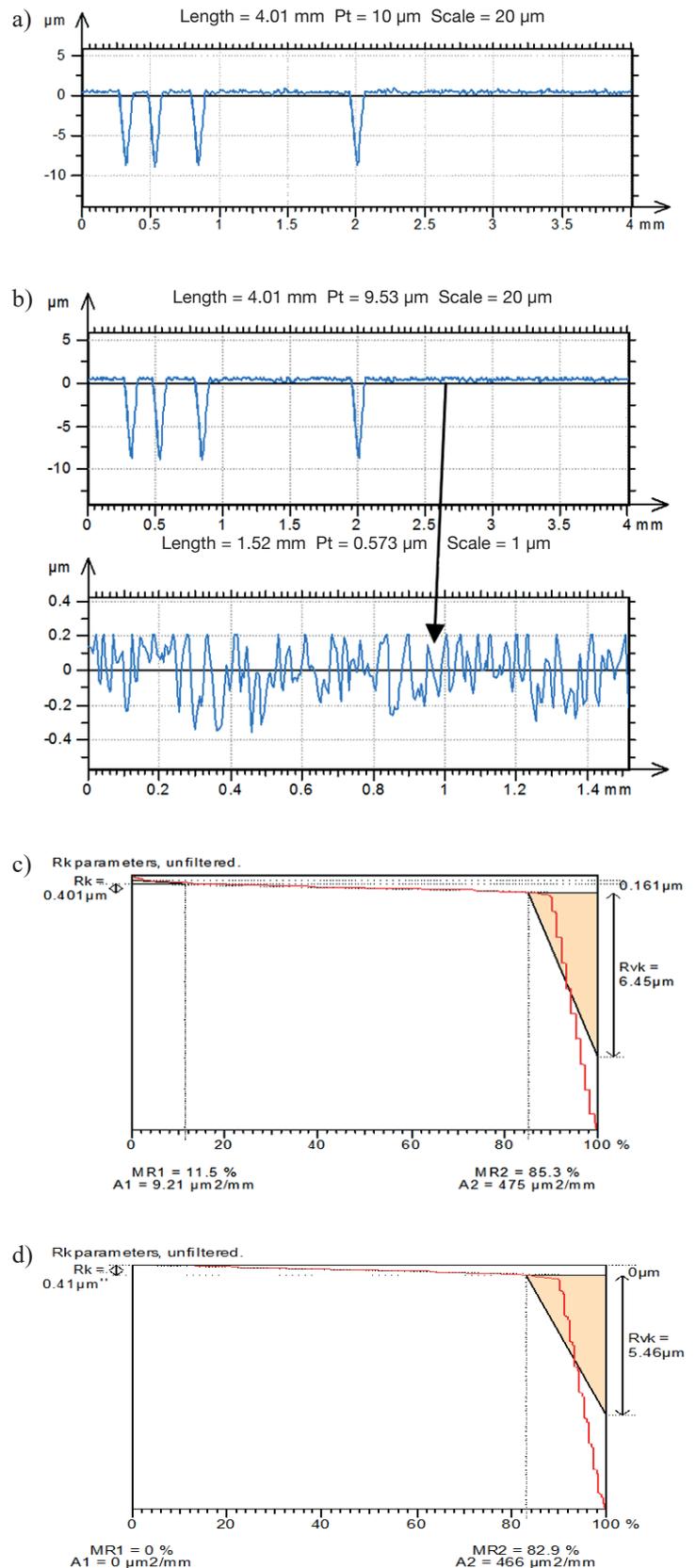

Fig. 4. Simulated unfiltered profile C (a), roughness profile filtered by the closing filter of 40 mm disk diameter and enlarged detail (b), material ratio of unfiltered profile (c) and material ratio of roughness profile (d)
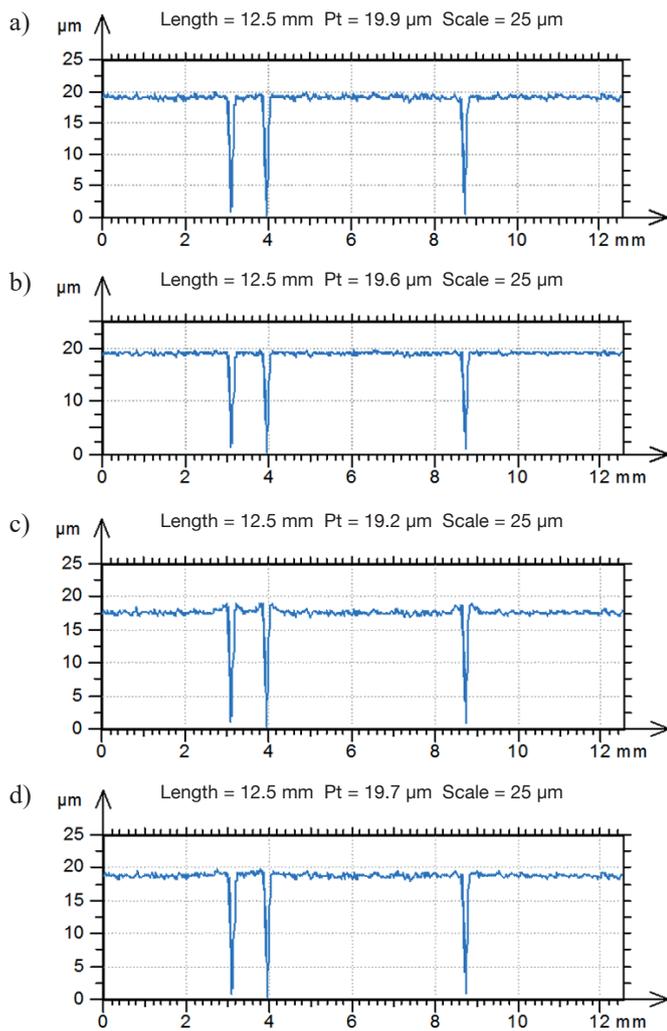
Fig. 5. Simulated unfiltered profile D – Pp = 1.18 μm, Pt = 9.6 μm (a), filtered by the alternating sequential filter of 60 mm disk diameter – Rp = 1.02 μm (b), filtered by the double Gaussian filter of 0.8 mm cut-off – Rp = 1.8 μm (c) and filtered by the double Gaussian filter of 2.5 mm cut-off – Rp = 1.29 μm (d)

decreased from 2.81 mm to 1.87 mm after application of the double Gaussian filter with 2.5 mm cut-off as well as after application of the morphological filter, while the RSm parameter decreased to 0.94 mm after usage of the Rk filter with 0.8 mm cut-off.

The form component needs to be removed from the profile before the Rk or robust filters could apply to the data. However, it was found after analysis of many simulated profiles with added curvatures that they didn't need to be preprocessed to form removal when the closing filter was used. This is important because not correct form removal can lead to a distortion of stratified textures [19].

The use of other morphological filters (dilation and sequential) led to disturbances of profiles near their edges. Robust spline filter and robust Gaussian filter of the second (and higher) order don't need to remove form. However these filters are not accessible in commercial software.

4. The analysis of measured profiles

For measured profiles of cylinder liner textures after plateau honing estimation of sizes of grooves seems to be difficult. However, widths of valleys can be determined using procedure describe in Reference [20]. Disk radius should be selected on the basis of a mean valley width (widths of valleys of measured profiles from plateau-honed cylinder surfaces are similar). Generally the proposed procedure of a disk radius of morphological filter selection was found to be very useful not only for simulated but also for measured profiles without substantial waviness. It can be also applied with good results for profiles with isolated dimples. Fig. 6 presents profile E containing a separate long oil pocket. After using the Rk filter the emptiness coefficient increased from 0.115 to 0.135, but after application of alternating sequential filter it decreased to 0.096. Decrease of the RSm parameter after morphological filter application was lower than that after using the double
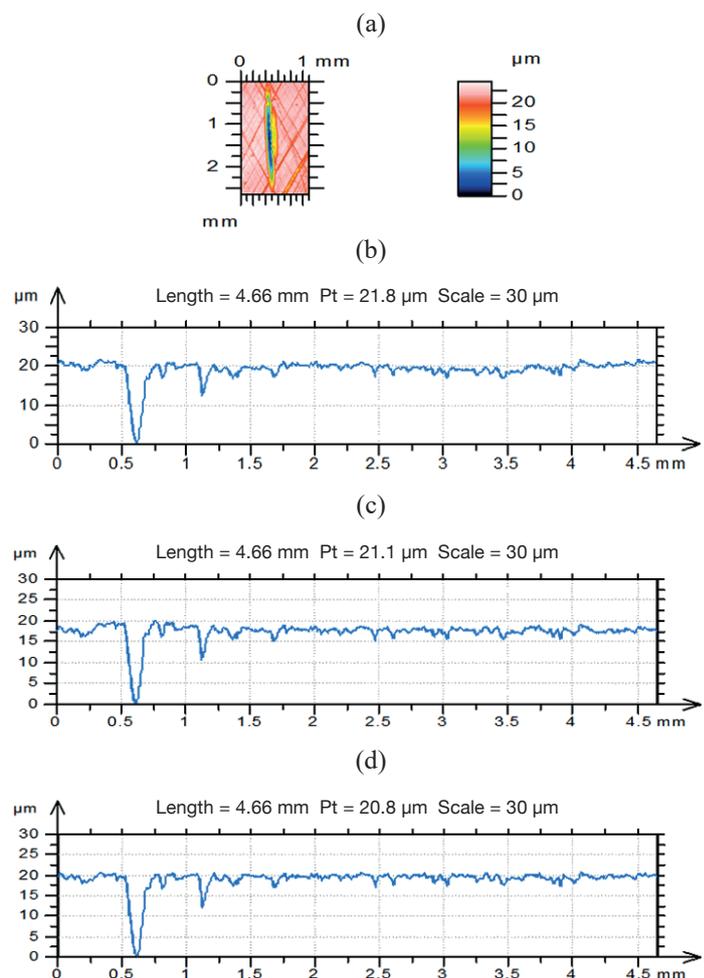

Fig. 6. Detail of contour map of cylinder profile with isolated oil pocket (a), extracted profile E containing dimple – Pp = 2.51 μm, PSm = 0.244 mm (b), filtered by the double Gaussian filter of 0.8 mm cut-off – Rp = 2.72 μm, RSm = 0.194 mm (c) and filtered by the alternating sequence filter of 46 mm disk diameter – Rp = 2 μm, RSm = 0.221 mm (d)

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Gaussian filter. One can see that the shape of the deep valley changed after the Rk filter application contrary to morphological filter use.

Unfortunately morphological filters are very sensitive to spikes [4]. Near a spike typically a depression is formed. Distortions were the smallest after using the sequential filter, from among morphological filters – see Fig. 7. Outliers should be eliminated before morphological filter application [21]. Contrary, the use of double Gaussian or robust Gaussian filter did not lead to profile distortion.

The procedure described in point 2 aims to select the smallest radius of disk being the structural element of the morphological filter. Application of this technique should not disturb roughness profiles of two-process surfaces. This radius depends mainly on widths of valleys and slightly on a height of the plateau surface portion; depths of valleys are unimportant. In the proposed procedure disk radius should be smaller for bigger height of the plateau profile part; however for one-process profiles it is typically larger for bigger roughness height. Therefore this procedure can be applied only to two-process textures containing wide valleys.

5. Conclusions

Digital filtration of simulated and measured two-process profiles using three kinds of morphological filters was studied. The original procedure of disk radius selection was elaborated. The procedure aims to select the smallest radius of disk not disturbing roughness profiles of two-process textures. This radius depends firstly on widths of valleys and secondly on the height of plateau surface part; depths of valleys are of smaller importance. The proposed procedure was found to be very useful for simulated and measured surfaces. It was developed for 2D profiles but could be easily extended for areal (3D) surface topography filtering. Behaviors of various morphological filters are different to that of valley suppression filter. Morphological filters application caused change of profile inside the wide valley, while the double Gaussian filter affected also valley neighbouring points. From among morphological filters, the alternating sequential filter is recommended. Morphological filters are very sensitive to spikes.
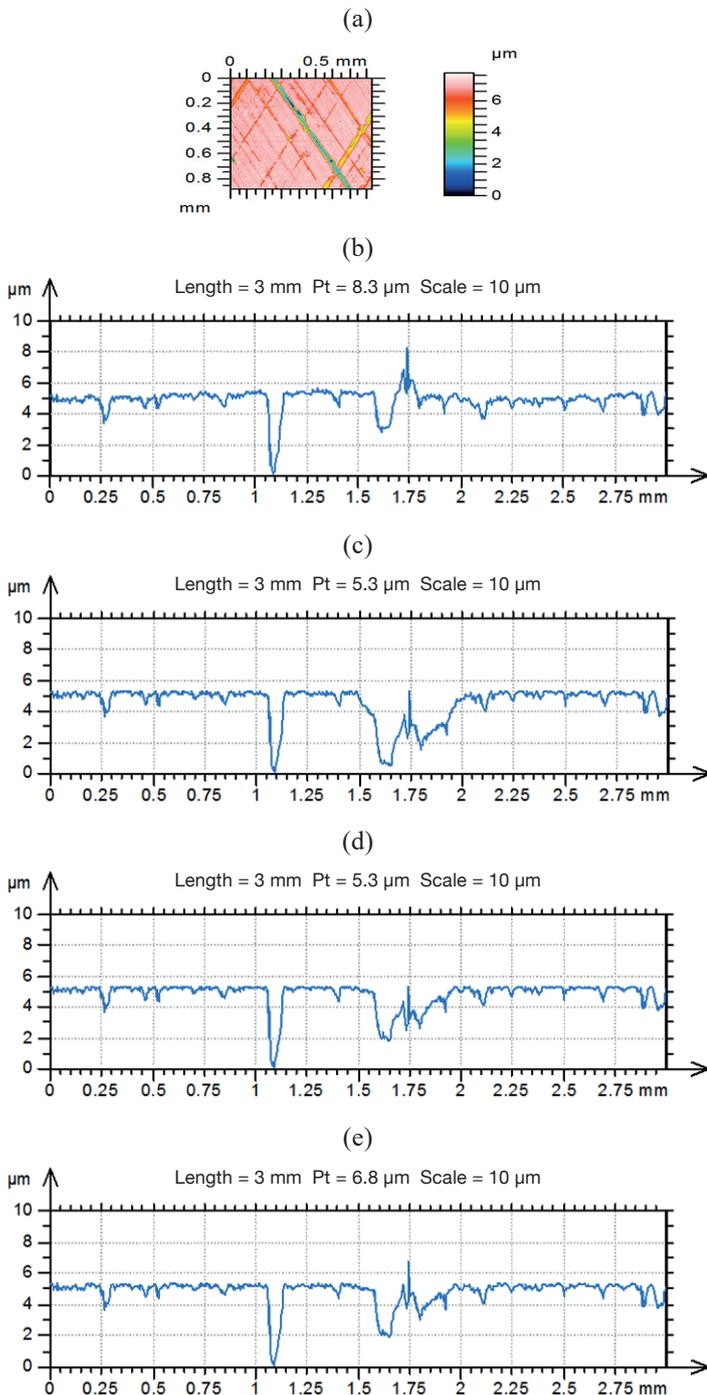
Fig. 7. Detail of contour map of plateau honed cylinder profile (a), extracted profile F containing spike (b), profile filtered by dilation filter of 22 disk mm diameter (c), filtered by the closing filter of 22 mm disk diameter (d) and filtered by the alternating sequence filter of 22 mm disk diameter (e)

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