BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES, Vol. 67, No. 2, 2019
DOI: 10.24425/bpas.2019.128597

The effect of valley depth on areal form removal in surface topography measurements

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Abstract. Surface topography assessments with valley exploration are of great importance. Two-process surfaces are often proposed for many combustion engines. One of the errors committed in surface topography measurements and analysis are those that occur during data processing. In this paper, improper areal form removal was taken into consideration for plateau-honed cylindrical surfaces with additionally burnished oil pockets. Usually, the reference plane is established by application of: fitting algorithms (e.g. cylindrical shape), polynomials, filters and other procedures. In many cases, the influence of the reference plane was not fully recognized during valley depth consideration. Moreover, the influence of areal form removal with edge-to-dimple and valley-to-dimple distances was not precisely defined. In this research, commonly used algorithms for form separation in surface topography analysis were proposed for the applications being considered. The digital filter bandwidth was also specified for valley depth analysis. The distortion of edge-located oil pockets was specified. It was assumed that application of robust techniques does not necessarily provide the desired results.

Key words: areal form removal, reference plane, two-process surfaces, surface topography, cylindrical surfaces.

1. Introduction

Surface topography is particularly important for the assessment of functional properties such as materials contact, lubricant retention or wear resistance. Due to the tremendous importance of surface texture for the functional parameters of machined parts, studies of measurement uncertainty in surface topography analysis should be regarded as particularly relevant. Detailed information about surface topography can be obtained by means of surface topography measurements and analysis. Errors in surface texture evaluation can be classified as measurement errors (measuring equipment and environment) [1–3], the measured object errors [4] as well as software and measuring method errors [5, 6]. Measuring uncertainty can be also categorized into errors: those typical for measuring methods, those caused by digitization process, those received during data processing and other errors [7–11]. The errors obtained during data processing can be divided into errors in reference plane selection [12] and errors in computing parameters. Surface topography analysis of car engine parts is functionally essential. A plateau-honed cylinder liner surface is an example of surface texture which consists of smooth plateaus with deep and wide valleys and is characterized by good sliding properties and lubrication maintenance. Surfaces containing dimples have a considerable advantage over one-process surfaces [13, 14]. However there are many problems in the studies on the results of measurement of stratified surface textures. Surface texture of cylindrical elements with additionally burnished oil pockets was analyzed already in [15, 16].

Plateau-honed cylinder surfaces belong to textured surfaces with oil pockets (dimples, valleys, holes) so they are often analyzed. The dimple can distribute a micro-hydrodynamic bearing by means of full or mixed lubrication. Moreover, valleys can provide a micro-reservoir oil protection when starved lubrication occurs. However, control of this type of surface texture requires an increase in significance of surface topography measurements and analysis. This entails judicious selection of the procedure for areal form removal. Even the most precise measurement cannot provide appropriate results when then digitization process (e.g. reference plane selection) is carried out erroneously.

Usually surface topography of cylindrical surfaces is analyzed after form removal [17]. There are many algorithms proposed for selection of the reference plane: fitted shapes (e.g. cylindrical) [18, 19], polynomials [20], digital filters [21], morphological techniques [22–25] and other methods [26]. It was assumed that application of a commonly used cylinder reference plane did not allow for correct form removal when the surface contained dimples [27]. Moreover, application of an extensively large degree of polynomial (greater than 2nd) caused the distortion of oil pockets. The higher the degree of polynomial that was applied, the larger distortion of dimples was noticed. For two-process surface filtering for waviness removal, the robust Gaussian regression filter was developed [28]. Procedures for valley extraction and/or digital fulfilling were also proposed [29].

In previous studies, the influence of valley depth would not be widely recognized while the reference plane was being selected; the effect of dimples distortion on incorrect specification of parameter values was not studied in a comprehensive manner. Moreover, the impact of dimples edge location was not taken into account when defining filter bandwidth (cut-off).

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Manuscript submitted 2018-04-19, revised 2018-06-08, initially accepted for publication 2018-06-26, published in April 2019.

2. Materials and methods

2.1. Analyzed surfaces and measuring equipment. Cylindrical surfaces having undergone the plateau-honing process were taken into consideration. The dimples were added by means of burnishing techniques and modelled in some cases. The width and average depth of oil pockets were between 0.5 and 0.8 mm and between 10 and 50 µm, respectively. More than 20 measured surfaces and 20 of them with added dimples were studied but few of them were showed in detail. Examples of analyzed surfaces are presented in Fig. 1. They were measured with the Talyscan 150 stylus instrument (nominal tip radius about 2 µm, height resolution about 10 nm) or with the white light Talysurf CCI Lite interferometer (height resolution 0.01 nm). The measurement was repeated three times and average values were taken into account (a method for surface measurement uncertainty determination was applied). The measured area was 3.35 mm by 3.35 mm.

2.2. Procedures of areal form removal. For selection of the reference plane, commonly used algorithms were proposed. The form was eliminated by: a cylinder fitted by means of the least square method (C_{LSM}); polynomials of 2nd and 4th degree (P_{2nd} and P_{4nd}, correspondingly); or filters: Gaussian regression filter (*GRF*) and robust Gaussian regression filter (*RGRF*).

Moreover, for minimization of oil pocket distortion, the procedure of valley (dimple) extraction (V_{EP}) was proposed. In this method, the valleys were detected by calculation of standard

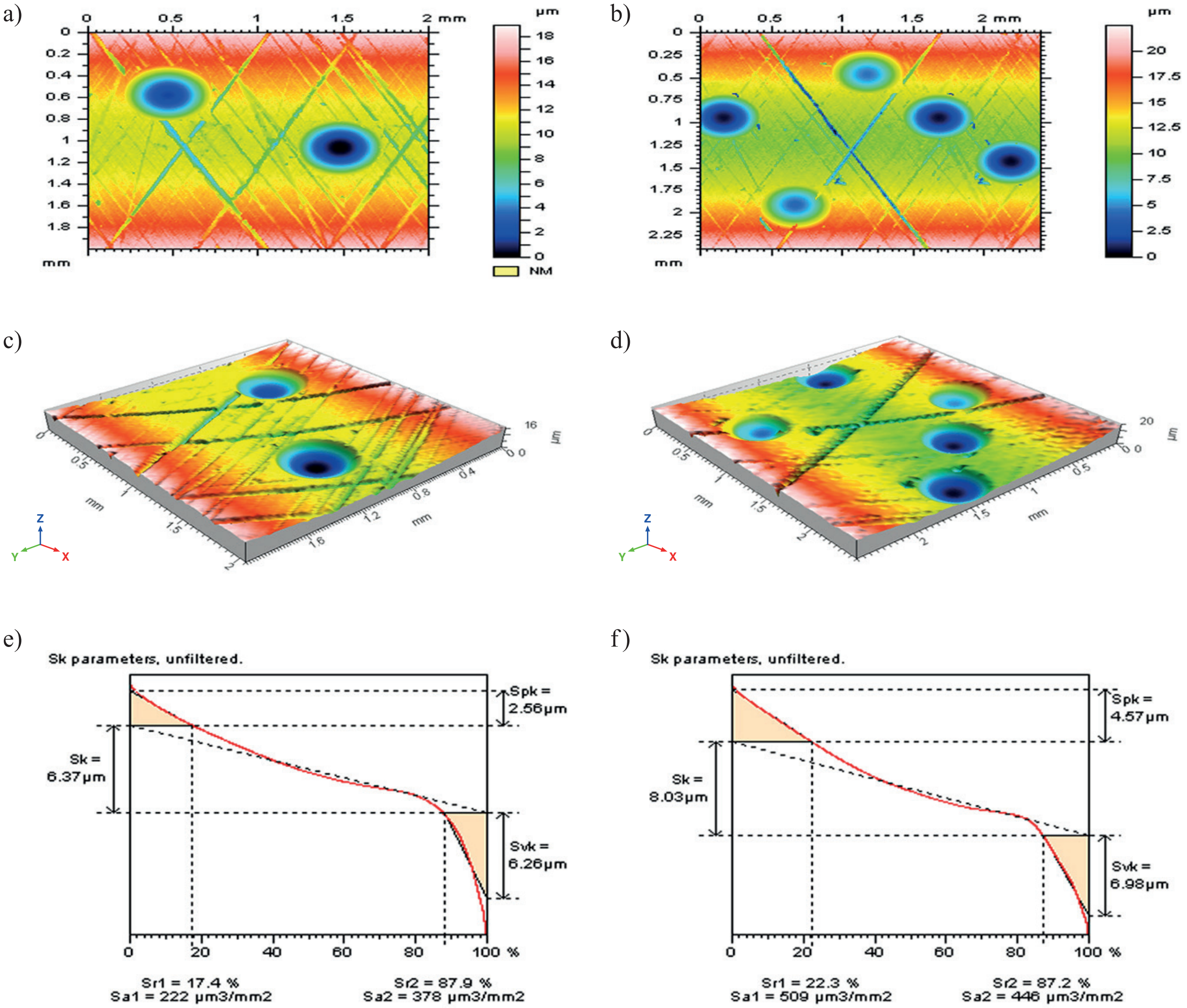


Fig. 1. Examples of details extracted from measured surfaces with added dimples: isometric view (a, b), contour plots (c, d) and material ratio curves (c, d), respectively

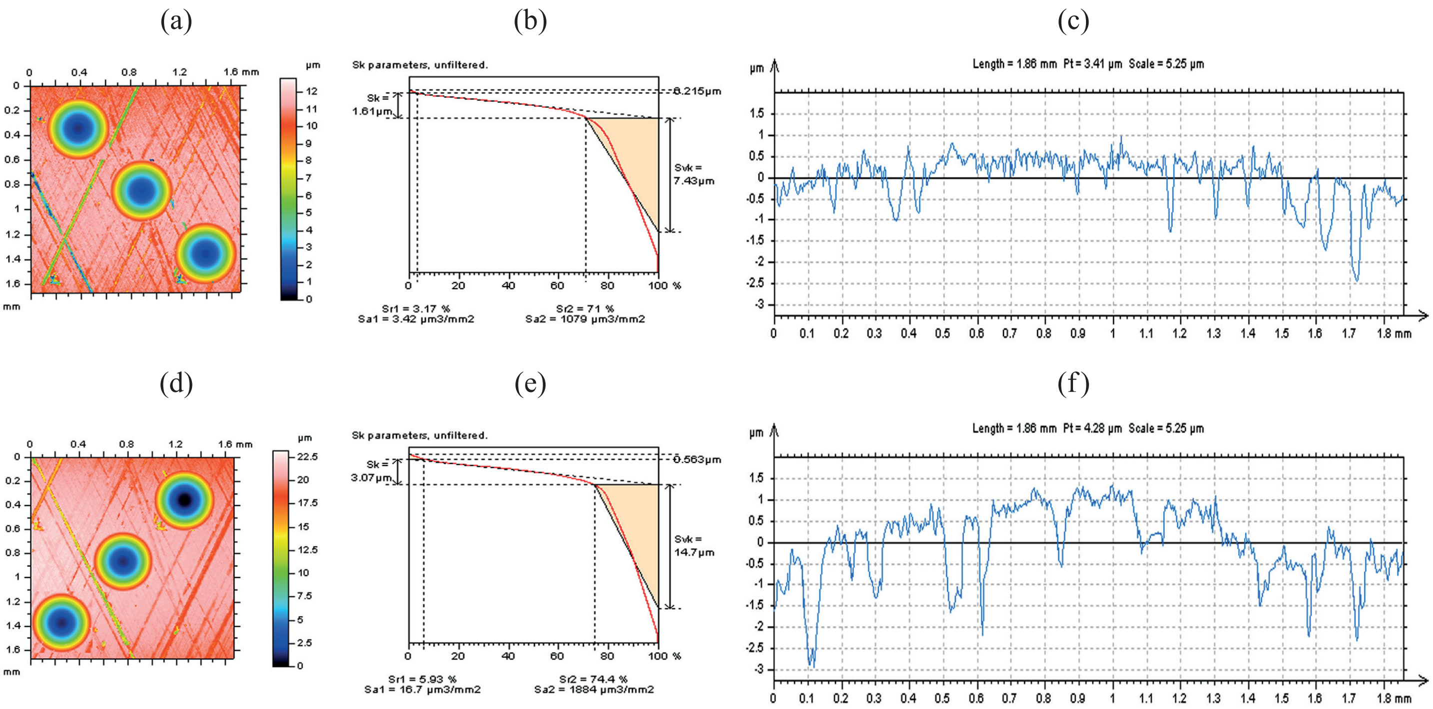


Fig. 2. Contour plots (a, d), material ratio curves (b, e) and extracted profiles (c, f) of surface with added dimples of average depth equal to: 10 µm (a) and 20 µm (b); after form removal by application of C_{LSM}

deviation for each measured point relative to the 8 neighboring points (it was defined for longitudinal profiles); the dimples were effected by the smooth shape subsequently.

Selection of filter bandwidth (F_{BD}) was also suggested with special attention to the edge-to-dimple (D_{ETD}) and valley-to-dimple (D_{VTD}) distance analysis. The influence of valley depth (V_{DP}) on areal form removal was taken into account. The effects of reference planes on surface views and parameters from the ISO 25178 standard were also studied.

3. Results and discussions

3.1. Problem of selection of reference plane with dimple analysis. Application of C_{LSM} did not allow to remove the form correctly (Fig. 2a and 2d), irrespective of V_{DP} values. When V_{DP} grew, the value of the Sk (core roughness depth) parameter also increased. Moreover, when $V_{DP} < 10$ µm, the position of the reference plane was not correctly specified; the surface was subjected to a levelling process before application of C_{LSM}. Accordingly to the increase of the Sk parameter, the value of Spk (reduced summit height) parameter also increased. False estimation of the reference plane (line) can be directly observed in contour plots (profile) exploration – Fig. 2a (Fig. 2c). Increase of the V_{DP} value caused the increase of reference plane selection irregularity. When the V_{DP} increased by 100% (from 10 µm to 20 µm in the example being presented) the value of the Spk parameter increased by 162% (from 0.215 µm to 0.563 µm) but the values of Sk and Svk parameters increased by 91% (from 1.61 µm to 3.07 µm) and by 97% (from 7.43 µm to 14.7 µm) correspondingly; and the values of parameters for plateau-part surface characterization increased. The values of: root mean square height Sq, maximum surface peak height Sp, maximum height Sz and arithmetic mean height Sa all grew by more than 50% when V_{DP} increased. Surface topography parameters for the surface after selection of the reference plane (by use of C_{LSM}, P_{2nd} and P_{4nd}) are presented in Table 1.

Table 1
Surface parameters following areal form removal by:
C_{LSM} (a1, b1), P_{2nd} (a2, b2) and P_{4th} (a3, b3)

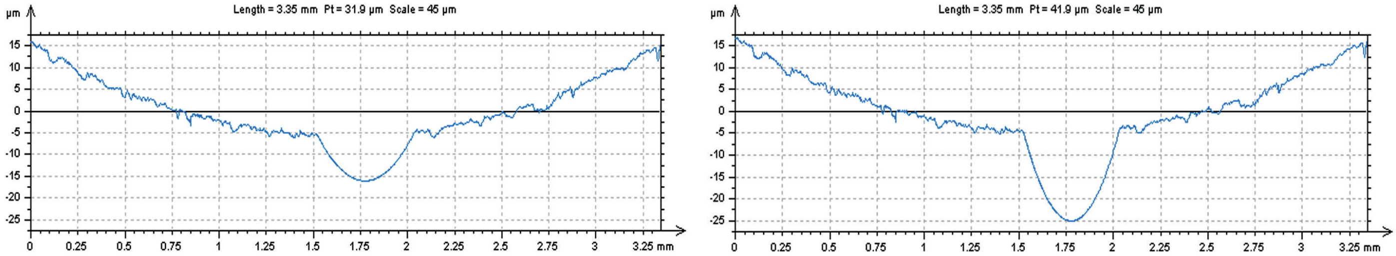
Parameters	$\mathbf{V_{DP} = 10}$ µm			$\mathbf{V_{DP} = 20}$ µm		
	***a*1**	***a*2**	***a*3**	***b*1**	***b*2**	***b*3**
Sq, µm	2.02	1.92	1.91	3.84	3.39	3.32
Sp, µm	3.15	2.82	2.97	5.03	3.64	4.36
Sv, µm	12.10	10.90	11.00	19.20	18.60	18.30
Sz, µm	15.30	13.70	13.90	24.30	22.30	22.60
Sa, µm	1.38	1.18	1.16	2.76	1.94	1.86
Sk, µm	3.06	1.85	1.95	5.31	2.96	3.10
Spk, µm	0.196	0.285	0.396	0.182	0.295	1.170
Svk, µm	4.77	5.15	5.41	7.00	9.15	10.30

For areal form removal, polynomials (commonly used in surface topography analysis) were proposed. Application of P_{2nd} caused a decrease of reference plane distortion as compared with C_{LSM}, despite the different value of V_{DP}. However, when

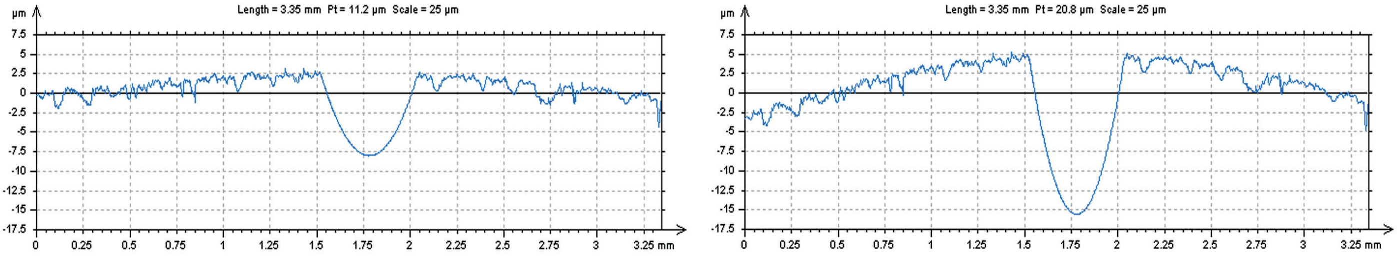
V_{DP} increased, the values of Sk and Spk parameters also increased. When the degree of the polynomial was augmented (regardless of the V_{DP} value), Sp, Sv and Sz parameters increased, Sq and Sa decreased, and the values of Sk parameters (Sk, Spk and Svk) also increased. Moreover, for surfaces containing dimples with the $V_{DP} > 10$ µm variation of Spk, the parameter increased significantly (even to 300%) when the degree of the polynomial was raised (from P_{2nd} to P_{4nd}). Application of C_{LSM} or polynomials (P_{2nd}, P_{4nd}) did not allow to unambiguously define the reference plane (results can be observed directly in the profile studies presented in Fig. 3). Therefor for areal form removal of cylindrical surfaces digital filtering (*GRF* and *RGRF*) of contacting oil pockets was proposed.

3.2. Errors of edge-to-dimple (edge-to-valley) areal form removal. From the analysis of surface isometric view, it was assumed that application of *GRF* with $F_{BD} = 0.8$ mm (as an L-filter for the long-wavelength components removal) caused serious distortion of dimples (Fig. 4a). Moreover, the area located between the valleys as well as the edge-section were not reliably estimated (this was indicated by arrows in Fig. 4a). The amount of dimple distortions was particularly noticeable with

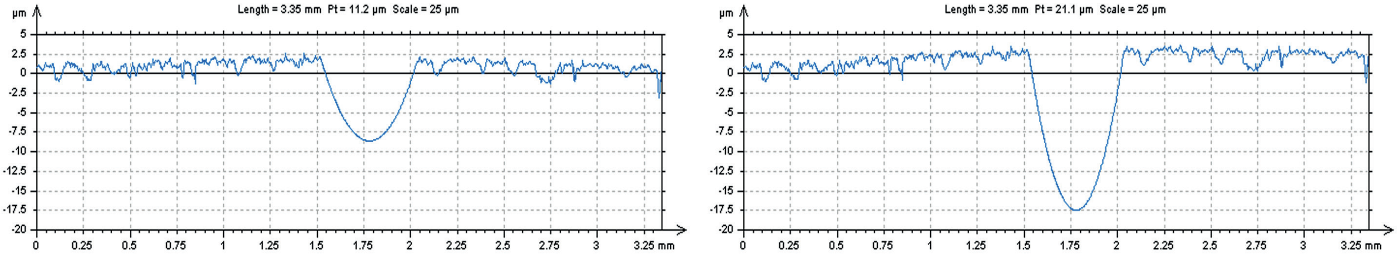
a) measured surface with added dimples; $V_{DP} = 10$ µm b) $V_{DP} = 20$ µm



c) after form removal by C_{LSM} – a1 d) b1



e) after form removal by P_{2nd} – a2 f) b2



g) after form removal by P_{4th} – a3 h) b3

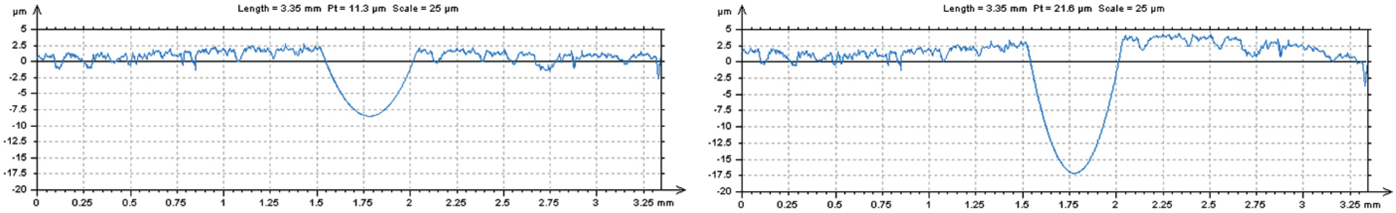
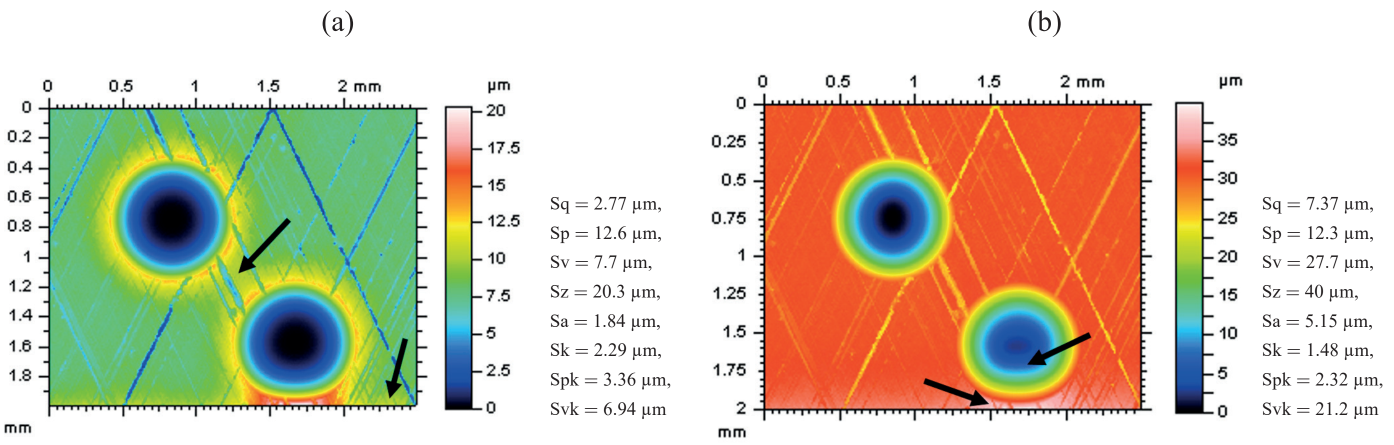


Fig. 3. Extracted profiles from surface before (a, b) and after (c, d, e, f, g and h) pre-processing


(a) (b)

Sq = 2.77 μm,
Sp = 12.6 μm,
Sv = 7.7 μm,
Sz = 20.3 μm,
Sa = 1.84 μm,
Sk = 2.29 μm,
Spk = 3.36 μm,
Svk = 6.94 μm

Sq = 7.37 μm,
Sp = 12.3 μm,
Sv = 27.7 μm,
Sz = 40 μm,
Sa = 5.15 μm,
Sk = 1.48 μm,
Spk = 2.32 μm,
Svk = 21.2 μm

Fig. 4. Details extracted (and their respective parameters) from surface after form removal by: a) *GRF*, and b) *RGRF*; $F_{BD} = 0.8$ mm

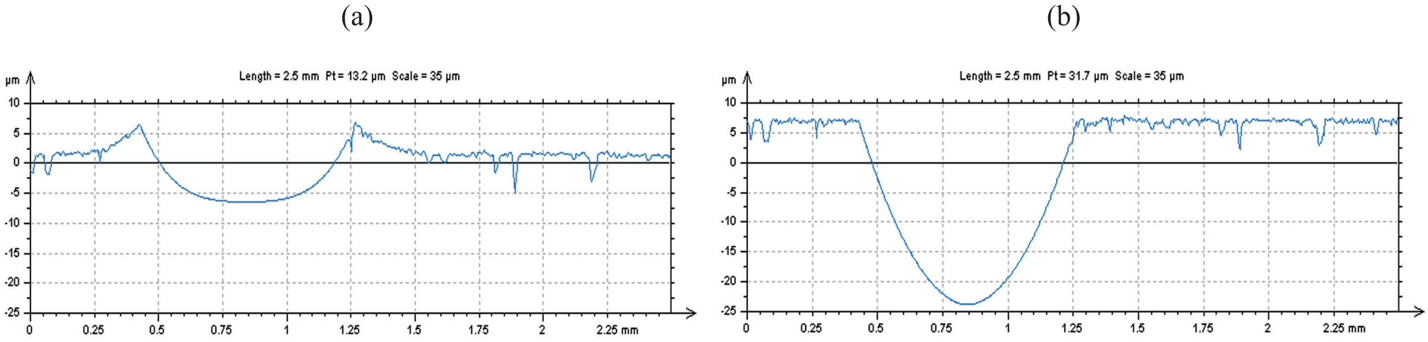

(a) (b)

Fig. 5. Profiles extracted from surface after form removal by a) *GRF*, and b) *RGRF*; $F_{BD} = 0.8$ mm

profile exploration, as in Fig. 5a; oil pockets were flatted and/or near-valley areas were vastly exaggerated.

For characterization of two-process surfaces, *RGRF* was developed and proposed [30, 31]. Application of this type of robust assessment caused a decrease in dimple misstatement (Fig. 5b). In comparison with *GRF*, the use of *RGRF* allowed for the following parameter value variations (related directly to valley evaluation): decrease of Sp, Sk and Spk and increase of Sv and Svk parameters. Some parameters changed significantly (Sv and Svk increased by 260% and 205%, respectively). However, the values of Sq, Sa and Sz parameters increased, which might have been caused by reduction of lubrication pockets pre-processing (selection of reference plane by means of filtering) and the resulting deformations.

Meanwhile, the usefulness of *RGRF* instead of *GRF* (with $F_{BD} = 0.8$ mm) in areal form removal of cylindrical surfaces containing deep and wide dimples was improved.

It was noticed that selection of the reference plane by RGRF was significantly impeded when dimples were edge-situated. Distortion of oil pockets as well as the edge-to-dimple area is indicated directly by means of arrows in Fig. 6. It was also found that valley deformation had a tendency to increase when $D_{ETD} < F_{BD}$; the smaller the value of D_{ETD} that was determined, the greater the distortion of dimples that was recognized. When $D_{ETD} > F_{BD}$, errors in selection of the reference plane were minimalized (Fig. 6a).

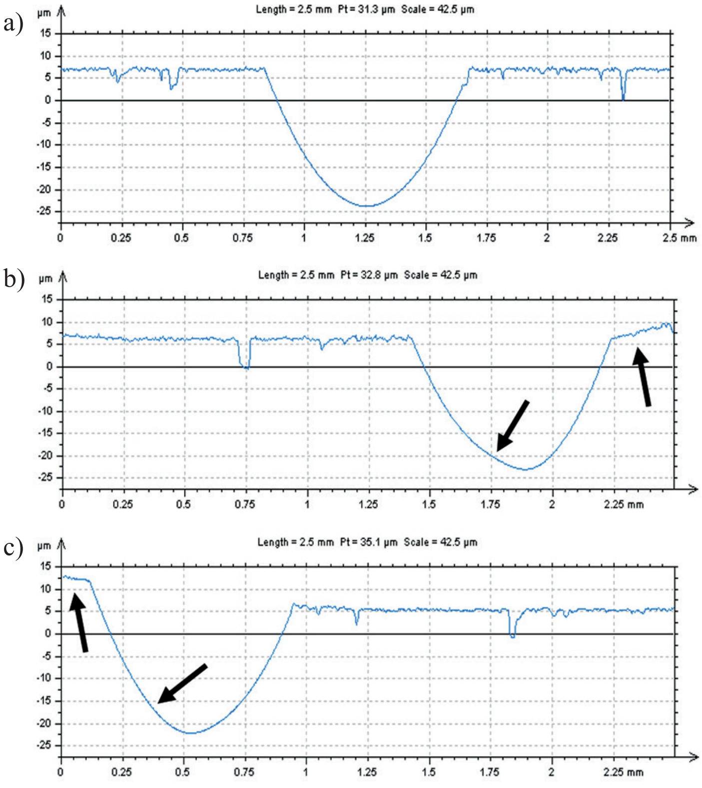


Fig. 6. Profiles from surface after usage of *RGRF* ($F_{BD} = 0.8$ mm)

3.3. Proposal of areal form removal with valley depth analysis. Selection of the reference plane was increasingly difficult when different values of dimple depth were taken into consideration. Analysis of surface topography with a specific range of the V_{DP} value (10 μm $< V_{DP} <$ 50 μm) was proposed (the range of depth coefficient was selected in accordance with a spectrum frequently used in engine cylinder liners).

It was found that areal form removal by application of polynomials caused glaring errors in dimple analysis when the degree was equal or higher than 4th. When P_{2nd} was applied, deformation of valleys was scarcely noticeable (generally did not occur); nevertheless, form was not entirely removed (Fig. 7a). When a digital filter was implemented (*GRF* or *RGRF*), distortions of dimples appeared (*GRF*) and robust techniques (*RGRF*) seemed to be an acceptable solution (Fig. 7b) except for the valleys with near-edge (smaller than F_{BD} value) distribution (an example was previously shown in Fig. 4b).

For minimization of oil pocket distortions, the procedure of valley extraction (V_{EP}) and further digital filtering (e.g. by *GRF*) were proposed. Application of V_{EP} for areal form removal by P_{2nd} caused the following changes in height parameters: Sp and Sk grew (by almost 50%), Spk decreased; and Sq, Sa, Sz, Sv and Svk parameters also increased. The value of lower bearing area (Sr2) decreased. Increment of Sv, Svk and Sz parameter values could be caused by reduction of oil pocket flattening. Functional parameters (area material ratio Smr and extreme peak height Sxp) increased except for the inverse areal material ratio (Smc) – the value of this particular parameter decreased. From among special parameters: auto-correlation length (Sal) grew but the texture-aspect ratio (Str) value was reduced. The texture direction (Std) as well as hybrid parameters (root mean square gradient Sdq and developed interfacial area ratio Sdr) remained permanent regardless of V_{EP} implementation in P_{2nd} areal form removal. Surface parameters following various (described) form removal techniques are presented in Table 2.

Table 2
Surface parameters following areal form removal by various methods

Parameters	**GRF**	**RGF**	**P_{2nd}**	**P_{4nd}**	**V_{EP} and application of:**		
					GRF	**P_{2nd}**	**P_{4th}**
Sq, μm	2.98	8.32	7.90	7.61	8.18	8.38	8.36
Sp, μm	10.20	6.61	7.46	9.35	5.89	6.66	6.63
Sv, μm	7.54	26.50	25.30	24.20	25.80	26.20	26.20
Sz, μm	17.8	33.1	32.7	33.5	31.7	32.9	32.8

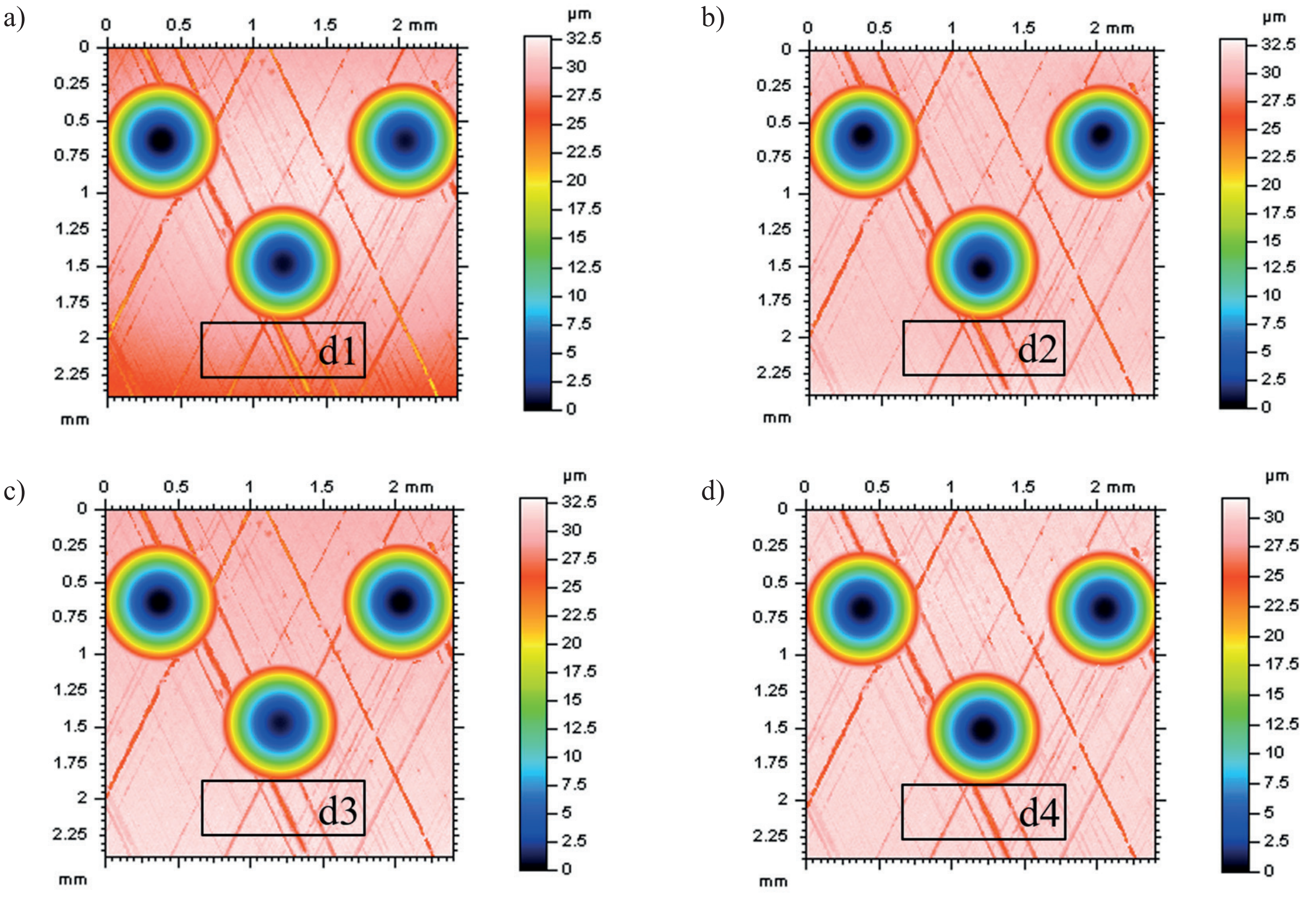


Fig. 7. Extracted part of surface after form removal by: P_{2nd} (a), *RGRF* (b) and application of V_{EP} with further use of P_{2nd} (c) and *GRF* (d); $F_{BD} = 0.8$ mm

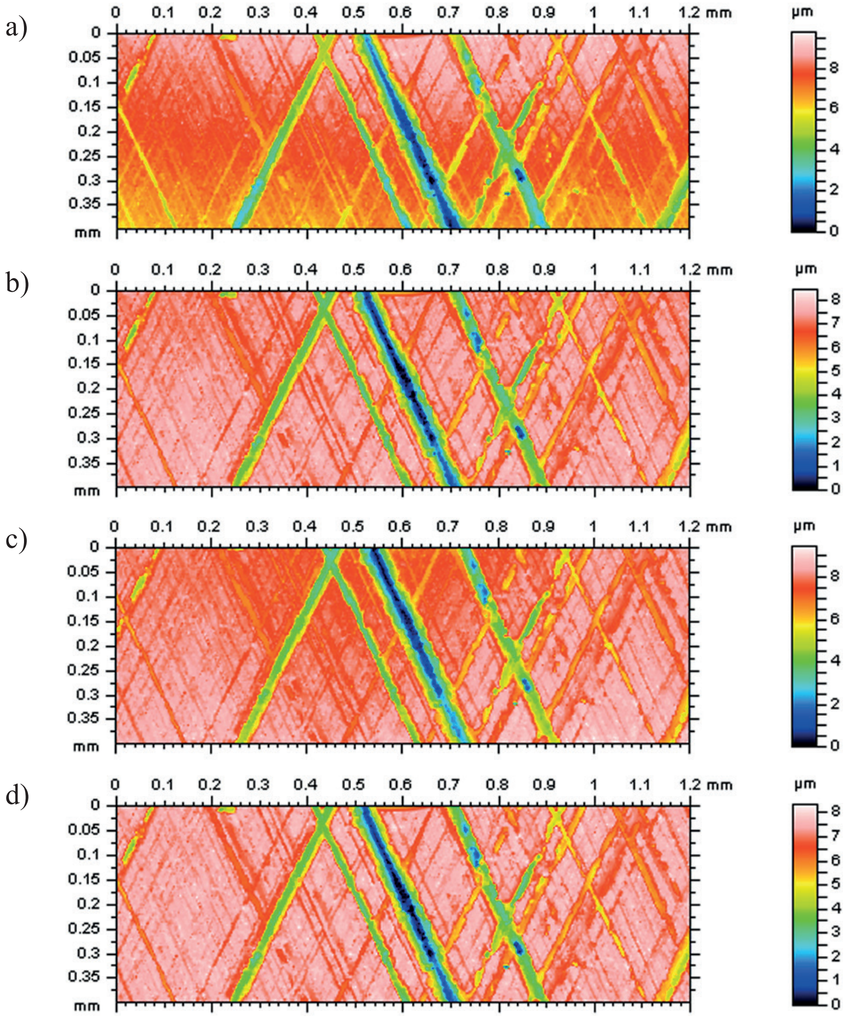
Parameters	GRF	RGF	P_{2nd}	P_{4nd}	V_{EP} and application of:		
					GRF	P_{2nd}	P_{4th}
Sa, µm	2.14	6.36	5.92	5.60	6.24	6.41	6.40
Sk, µm	2.95	1.66	6.62	11.30	1.17	3.55	3.45
Spk, µm	3.050	0.461	0.224	0.607	0.257	0.179	0.197
Svk, µm	7.14	23.0	22.5	19.7	22.1	24.6	24.5
Sr2, %	76.6	62.9	73.6	80.1	61.2	68.6	68.3
Smr, %	0.0146	0.9860	3.1300	0.9740	9.0900	5.9100	5.6600
Smc, µm	6.85	1.55	1.49	2.17	1.01	1.14	1.15
Sxp, µm	7.67	27.60	25.40	23.20	27.30	27.30	27.30
Sal, mm	0.250	0.382	0.359	0.34	0.374	0.381	0.381
Str	0.927	0.797	0.829	0.856	0.777	0.705	0.710
Std, °	116	116	116	116	116	116	116
Sdq	0.115	0.159	0.159	0.159	0.159	0.159	0.159
Sdr, %	0.65	1.21	1.21	1.21	1.21	1.21	1.21

When P_{4nd} was applied with V_{EP}, most of the values of height parameters decreased (with regard to P_{2nd}) except for the Spk parameter (which increased by 10%).

The results of regular robust filtering (*RGRF*) were compared to the commonly used Gaussian regression filter (*GRF*) applied with previously used valley extraction procedure (V_{EP}); $F_{BD} = 0.8$ mm. Usage of V_{EP} and then *GRF* caused minimization of the Sk parameter value (Sk decreased by 30% as compared with regular *RGRF*). Moreover, the Sq, Sp, Sz, Sa and Spk parameter values decreased by 2%, 11%, 4%, 2% and 44%, respectively.

The results of filtering of free-of-dimples surface parts are also sufficiently precise after application of V_{EP} with *GRF*; the smallest values of Sp and Sz parameters were obtained (Fig. 8).

For $D_{VTD} < F_{BD}$, the deformation in near-valley and/or near-dimple areas increased when *RGRF* was applied; the smaller the D_{VTD} value that was noticed, the larger the distortion that was recognized. The influence of V_{EP} application on minimization of reference plane distortion can be closely observed in profile exploration. Examples of profiles with valley-to-valley and valley-to-dimple detail analysis are presented in Fig. 9 (areas of unsuitable reference plane position are indicated by the arrows).



a) Sq = 1.48 µm, Sp = 2.66 µm, Sv = 7.13 µm, Sz = 9.79 µm, Sa = 1.05 µm

b) Sq = 1.36 µm, Sp = 1.78 µm, Sv = 6.69 µm, Sz = 8.47 µm, Sa = 0.946 µm

c) Sq = 1.45 µm, Sp = 2.08 µm, Sv = 7.38 µm, Sz = 9.46 µm, Sa = 0.991 µm

d) Sq = 1.36 µm, Sp = 1.65 µm, Sv = 6.69 µm, Sz = 8.34 µm, Sa = 0.943 µm

Fig. 8. Details: d1 (a), d3 (b), d2 (c), d4 (d) and their parameters (correspondingly) from surface after selection of reference plane by alternative pre-processing techniques (descriptions in Fig. 7)

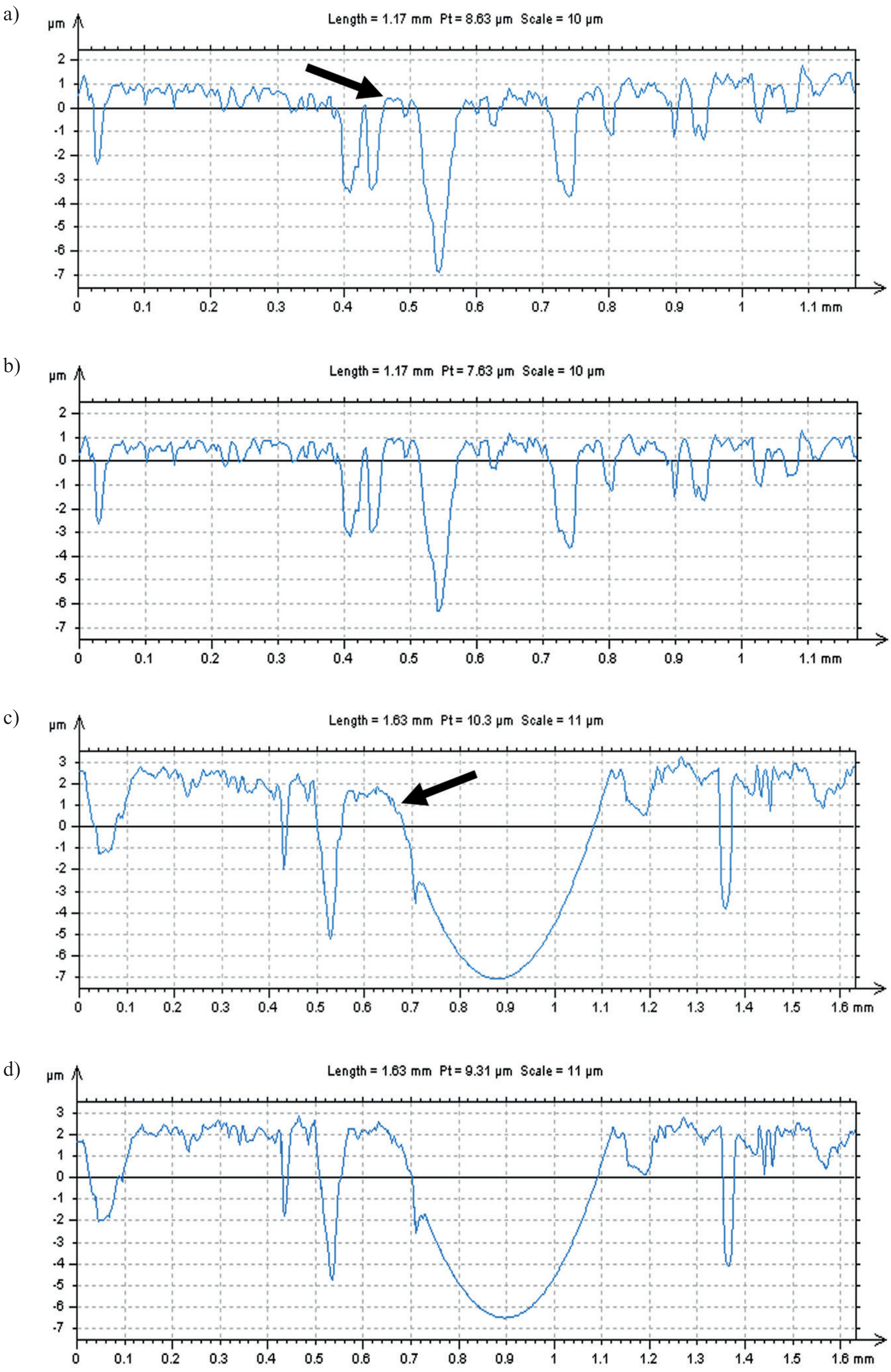


Fig. 9. Surface profiles following selection of reference plane by: *RGRF* (a, c) and application of V_{EP} with *GRF* (b, d); $F_{BD} = 0.8$ mm

4. Conclusions

It is very difficult to determine a comprehensive solution for areal form removal of cylindrical surfaces. However, the following conclusions were proposed:

1. Application of a cylinder (fitted by the least square method) did not allow to remove form correctly when the surface contained dimples (even when the depth of the valley was smaller than 10 μm).
2. Polynomial form removal (2nd or 4th degree) caused a decrease of reference plane distortion as compared with cylinder form removal despite the different value of valley depth. However, increase of valley depth affected the growing errors of reference plane selection.
3. For two-process surfaces, robust Gaussian regression filter was proposed. Usage of this type of pre-processing techniques provided encouraging results for areal form removal. However, application of regular robust regression filtering caused the distortion of dimples when they were located near the edges (deformation occurred when the edge-to-dimple distance was smaller than the filter cut-off value).
4. For minimization of distortion of edge-distributed oil pockets, the valley excluding method was proposed. Further application of digital filtering (e.g. the commonly used Gaussian regression filter) allowed to reduce the deformation of dimples; compared with robust regression filtering, edge-to-dimple distance can be smaller than filter bandwidth. In further research, the influence of edge-to-scratches distances on selection of the reference plane should be taken into account.
5. Application of the valley excluding method with polynomial areal form removal can be fairly effective regardless of valley depth values (even when the depth of dimple is higher than 10 μm); it can be applied for selection of the reference plane with deep and wide valley analysis.
6. For areal form removal of cylindrical surfaces containing wide and/or deep valleys (created by burnishing techniques) application of the valley excluding method and further usage of digital filtering is suggested instead of robust regression filtering or cylinder fitting and polynomial approaches; the method proposed can provide better robustness for the distortion of dimples when the distance between oil pockets and/or the oil pocket and the edge of the surface is small (the value of distance was analyzed and determined depending on the filter bandwidth value).

Acknowledgements. This paper was prepared with financial support from the National Science Centre, project No. 2013/09/N/ST8/04333.

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