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THE EFFECT OF REFERENCE PLANE ON VALUES OF AREAL SURFACE TOPOGRAPHY PARAMETERS FROM CYLINDRICAL ELEMENTS

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Abstract

In this paper distortion of surface topography measurement results by improper selection of the reference plane is taken into consideration. The following types of surfaces from cylindrical elements were analyzed: cylinder liners after plateau honing, cylinder liners with additionally burnished oil pockets and turned piston skirts. Surface topographies of these elements after a low wear process were also studied. In order to obtain areal surface topography parameters, the form was eliminated using cylinders and polynomials of the following degrees: 2, 3, 4, 6, 8, 10 and 12. Parameters of surfaces after form removal were compared. After analysis of results the reference elements for each kind of surface were recommended. A special procedure was proposed in order to select the degree of a polynomial. This method is based on surface topography changes with increase of polynomial degree. The effect of improper form elimination on measuring uncertainty was studied.

Keywords: surface topography, reference element, cylinder liners, oil pockets, piston skirts.

1. Introduction

Surface topography is generated in the last stages of a machining process. Very important functional properties, such as materials contact, sealing, friction, lubricant retention and wear resistance are related with surface topography. Surface topography measurement is the process which gives quantitative information about surface topography. Due to substantial influence of surface texture on functional parameters of machined parts, analysis of the measurement uncertainty in surface morphology is a task of great practical importance.

Internal combustion (IC) engines are widely used in a variety of their applications. Since they consume fuel and contribute to air pollution, the attempts of reducing IC engine fuel consumption and emissions have high priorities of the automotive industry. From the total fuel energy, up to 15% is lost in mechanical friction but almost half of it comes from the piston assembly-cylinder liner configuration. The oil consumption is mainly caused by the engine's piston-piston rings-cylinder liner system. Therefore parts of this system should be subjected to special control in the process of surface metrology.

There are many factors affecting uncertainty in surface geometry measurement. They are caused by the environment, measuring equipment, the measured object, software and measuring method [1, 2, 3, 4, 5, 6, 7]. There are the following kinds of measurement uncertainty: errors typical for the measuring method, errors caused by the digitisation process, errors obtained during data processing and other errors. The initial assessment of surface topography was made simply by running a fingernail across the surface [2]. This technique survives to this day as a tactile comparison. This type of measurement is widely known because of an almost 70-year history, therefore the sources of uncertainty of surface texture

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measurement are commonly known. Errors typical for surface topography measurement using a stylus instrument were described in [8]. Recently, surface measurement using optical techniques became very popular. Optical measurement suffers from the same intrinsic constrains as the stylus technique but also has an additional problem scattered light from the surface does not entirely react normally to the surface which restricts optical use in some applications [9].

The errors obtained during data processing can be divided into errors in establishing the reference element and errors of computing parameters. An assessment of surface topography by surface parameters is useful when long wavelength components are removed from the measured surface data. Unwanted elements of the surface geometry are commonly referred to waviness due to imperfections in the manufacturing process. A necessary preliminary to numerical assessment of surface profiles is to extract the frequency components representative of the roughness and to eliminate those that would be irrelevant. Separation of the texture profile from the waviness can be done by positioning a reference mean line. Methods of profile filtering are described in Reference [10]. Digital filtration of areal surface topography are more complicated. Robust filters seem to be the best possibility [11, 12, 13].

An alternative approach of filtering is to utilize all the data and to fit some kind of best fit reference element (line for 2D profiles and plane for 3D surface topography). The initial, but substantial operation during analysis of areal surface topography is selection of the reference plane. By its improper choice serious errors in parameter calculation can arise. Although there are some requirements to select a digital filter, such specifications are absent for selection of the reference plane. Because the whole surface topography of an element co-acts with another element under frictional conditions (not selected wavelengths), often before the analysis only the form was removed. Only a few technical publications were found on this subject. The authors of paper [4] proposed to use a polynomial of second degree to remove the form of curved surfaces.

Multi-process surfaces are functionally important. Plateau honed cylinder texture is a typical example of such surfaces. It consists of smooth wear-resistant and load-bearing plateaus with intersecting deep valleys working as oil reservoirs and debris trap. Plateau honed cylinder surfaces belong to textured surfaces with oil pockets (dimples, holes, cavities). The dimple can serve either as a micro-hydrodynamic bearing in cases of full or mixed lubrication, a micro-reservoir for lubricant in cases of starved lubrication conditions or a micro-trap for wear debris in either lubricated or dry sliding [14, 15]. The problem is that control of such surface texture requires a complementary response from surface metrology. It concerns the selection of reference elements and characterization. Without an adequate measurement technique the control and hence any attempt to maintain quality is lost. It was found that improper selection of reference planes can cause wrong estimation of dimple sizes [16].

2. Materials and methods

Three types of surface topographies of cylindrical elements, originating from the piston-piston rings-cylinder liner system of an internal combustion engine, were analyzed: cylinder liners after plateau honing, cylinder liners with additionally burnished oil pockets and turned piston skirts. Surface topographies of these elements after a low wear process (wear within the limits of machined surface topography) were also analyzed. Generally 30 surfaces were taken into consideration. They were measured by Talyscan 150 stylus equipment (nominal tip radius about 2 μm, height resolution about 10 nm) and white light interferometer Talysurf CCI Lite (height resolution 0.01 nm). In order to obtain areal (3D) surface topography parameters, the form was eliminated by cylinder and polynomials of the following degrees: 2, 3, 4, 6, 8, 10 and 12 using TalyMap Gold software. Parameters from the ISO 25178-2 standard and from the 3D extension of standard ISO 13565-2 (*Sk* family: reduced summit height *Spk*, reduced valley depth *Svk*, core roughness depth *Sk*, upper bearing area *Sr1* and lower bearing area *Sr2*) were studied and compared with surfaces with removed curvatures. Digital filters were not used.

3. Results and their analysis

3.1 Plateau–honed cylinder surfaces

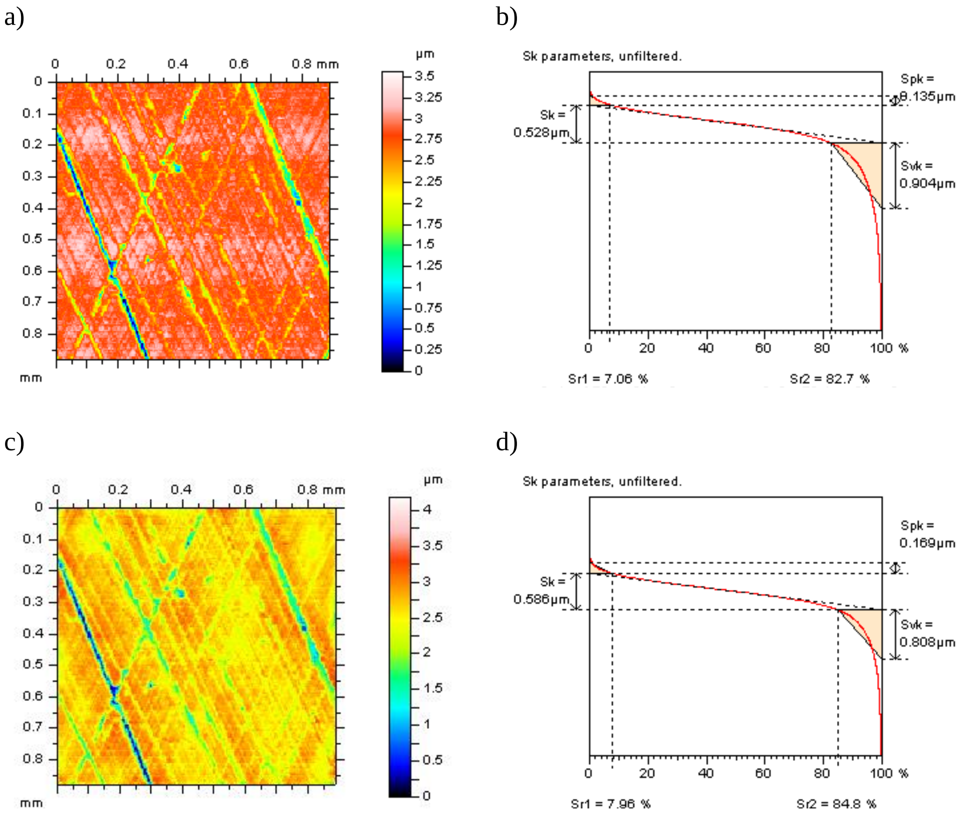
From the analysis-of-surface view it was found that application of the cylinder as the reference element did not allow to correctly eliminate the form. The statistical amplitude parameters were much higher than those obtained after using polynomials. Increase of the polynomial degree in form elimination caused a decrease in statistical height parameters, spatial parameters texture-aspect ratio *Str* and auto-correlation length *Sal* and usually an increase of summit density *Spd*. The texture direction *Std* parameter was constant independently of the kind of the reference plane, the effect of form removal on parameters such as the root mean square slope *Sdq*, developed interfacial area ratio *Sdr* as well as arithmetic mean peak curvature *Spc* was negligible.

The change of the rough core Sk is interesting, especially for cylinder surfaces containing deep and wide valleys. Initially during an increase of the polynomial degree the Sk parameter decreased. However, when the degree of the polynomial was higher than 3 or 4, this parameter started to increase. This change is connected with increase in the maximum peak height Sp parameter, increase in the skewness Ssk and sometimes increase in maximum height, decrease in parameters characterizing maximum valley depth Sv and Svk and decrease of kurtosis Sku. As the consequence, the emptiness coefficient Sp/Sz increased, its changes could be substantial. Improper estimation of parameters Sk, Sp/Sz and Ssk is of great importance; it was found that oil emission by the engine was proportional to the core roughness Sk [17] and cylinder wear under various conditions was proportional to the emptiness coefficient Sp/Sz [18, 19]. The Svk parameter is also within the requirement of the leading engine builders, since it is connected with oil capacity; cylinders whose surfaces are characterized by a small Svk value have an inclination to seizure. Material ratio Sr2 increased during an increase of the degree of a polynomial. The oil capacity Sa2 is equal to 0.005 Svk (100-Sr2). It can be highly underestimated for too high degree of a polynomial due to increase of the material ratio Sr2 and decrease of the Svk parameter. As the result of improper form removal, cylinders with required surface topography can be considered as spoilages, which leads to increase of production costs. Use of too high polynomial degree caused results similar to the application of a Gaussian filter for stratified surface topographies.

Figure 1 presents a comparison of contour plots of cylinder liner detail after using a polynomial of 3rd and 12th degree as the reference plane. Increase of the polynomial degree from the third to twelfth caused an increase of the *Sk* parameter by 11%, a similar decrease of the *Svk* parameter, decrease of skewness *Ssk* and kurtosis *Sku*, increase of *Sp* by almost 100%, small decrease of *Sv* and increase of *Sz* by 17%. Because the *Sp* parameter increased, the emptiness coefficient *Sp*/*Sz* increased by 65%.

As evident, the changes of selected parameters and the errors of parameter computation of plateau-honed cylinder surface textures can be large, especially for wide and deep valleys. Increase in the core depth *Sk* and decrease in the *Svk* parameter are most probably connected with valley depth, decreasing during an increase of the polynomial degree. This phenomenon will be further analyzed for cylinder surfaces containing dimples created by the burnishing technique. During selection of the polynomial degree it is recommended to increase it and analyze changes of height parameters and parameters from the *Sk* family. It is necessary to choose the degree from which the *Sk* and *Sp* parameters start to increase. If no such changes were found, a polynomial degree should be selected from which changes in statistical amplitude parameters become small during an increase of the degree of a polynomial. Similar results were obtained with regard to cylinder surfaces after low wear.

After analysis of a lot of cylinders the present authors propose to use a polynomial of the third or fourth degree.



e)

Sq = 0.381 µm
Ssk = - 2.74
Sku = 13.8
Sp = 0.81 µm
Sv = 2.76 µm
Sz = 3.57 µm
Sa = 0.245 µm

f)

Sq = 0.358 µm
Ssk = - 2.34
Sku = 12.2
Sp = 1.61 µm
Sv = 2.58 µm
Sz = 4.19 µm
Sa = 0.239 µm

Fig. 1. Surface contour plots (a, c), material ratio curves (b, d) and selected height parameters (e, f) of plateau honed cylinder surface after form removal by degree of a polynomial: 3 (a, b, e) and 12 (c, d, f).

3.2. Plateau-honed cylinder surfaces with added oil pockets created by the burnishing technique

In order to improve the tribological properties of friction pair: cylinder liner – piston ring, the plateau honed cylinder liners were subjected to burnishing. In such technique, special endings acted as hammers to form dimples on the machined surface. As a result of texturing, the randomly distributed dimples were added. The depth of oil pockets was 5 µm on the average, but the pit-area ratio was about 13%. The dimple depth was much smaller than for dimples analyzed in [16], therefore other effects of their presence can arise. An increase of

the degree of a polynomial caused a decrease of average height parameters arithmetic mean height *Sa* and root mean square height *Sq* and decrease of spatial parameter Sal and frequently *Str*. The texture direction *Std* was constant independently of the reference element. Similarly to plateau-honed cylinder surfaces, the effect of the reference plane on the parameters *Sdq* and *Sdr* was negligible. However the core roughness depth *Sk*, material ratio *Sr2* and sometimes the maximum surface peak height *Sp* or maximum height *Sz* increased when the degree of a polynomial was higher than 2 or 3 (depending on the surface) during an increase of the degree of a polynomial. Similarly to plateau honed cylinders the skewness *Ssk* has a tendency to increase but the kurtosis *Sku* to decrease when the core roughness depth increased.
Table 1 presents the values of selected parameters obtained after using various reference planes. It is evident that the *Sk*, *Ssk* as well as *Sr2* parameters started to increase from the 2nd degree of the polynomial. However *Sz*, *Sv* and *Svk* parameters decreased. Figure 2 presents contour plots and the material ratio curve from this surface after using polynomials of the 2nd and 8th degrees.

Table 1. Parameters of plateau-honed cylinder surface with burnished oil pockets for various reference planes.

Parameters	Polynomial of 2nd degree	Polynomial of 3rd degree	Polynomial of 4th degree	Polynomial of 6th degree	Polynomial of 8th degree	Polynomial of 10th degree	Polynomial of 12th degree
Sq, µm	1.61	1.55	1.51	1.34	1.17	1.03	0.93
Ssk	-1.83	-1.62	-1.23	-0.67	-0.46	-0.42	-0.61
Sku	7.31	6.64	5.89	5.26	4.63	5.44	6.35
Sp, µm	7.73	7.52	7.71	7.22	6.65	6.66	6.33
Sv, µm	8.97	8.33	7.94	7.62	7.37	7.69	7.56
Sz, µm	16.7	15.8	15.6	14.8	14,0	14.4	13.9
Sa, µm	1.05	1.03	1.03	0.95	0.86	0.75	0.67
Sal, mm	0.0774	0.0743	0.0709	0.0632	0.0505	0.0431	0.0381
Str	0.941	0.896	0.881	0.931	0.739	0.745	0.731
Std, °	119	119	119	119	119	119	119
Sdq	0.43	0.43	0.43	0.43	0.43	0.43	0.43
Sdr, %	8.35	8.35	8.35	8.35	8.35	8.34	8.34
Spd, 1/mm^2	1117	1299	1363	1575	1885	1760	2014
Spc, 1/mm	2.14	2.06	2.04	1.96	1.91	1.93	1.87
Sk, µm	1.67	1.85	2.08	2.37	2.38	2.08	1.83
Spk, µm	1.27	1.32	1.47	1.58	1.31	1.26	1.09
Svk, µm	4.16	3.92	3.44	2.56	1.95	1.56	1.47
Sr2, %	79.8	81.2	82.2	85.5	87.1	86.8	86.6

The shapes of oil pockets after using various reference planes are also presented in Figure 2. When the degree of a polynomial increased, the *Svk* parameter decreased by 53%, but the *Sk* parameter increased by 42.5%. Material ratio *Sr2* also increased, similarly to the plateau honed cylinder surface shown in Figure 1. Therefore, the oil capacity *Sa2* decreased by 70%. The analysis of a singular dimple is helpful to explain the observed behavior. As the result of the increase of the polynomial degree, the dimple depth decreased from 8.5 µm to 6.25 µm. For an undistorted surface the dimple almost entirely belongs to the valley part. When the degree of a polynomial increased, the upper part of the oil pocket is transferred to the core part of surface texture; therefore the core roughness height *Sk* increased. A similar situation takes place with regard to a plateau honed cylinder surface; however, the effect of polynomial increase is not so substantial, because the valley sizes are smaller.

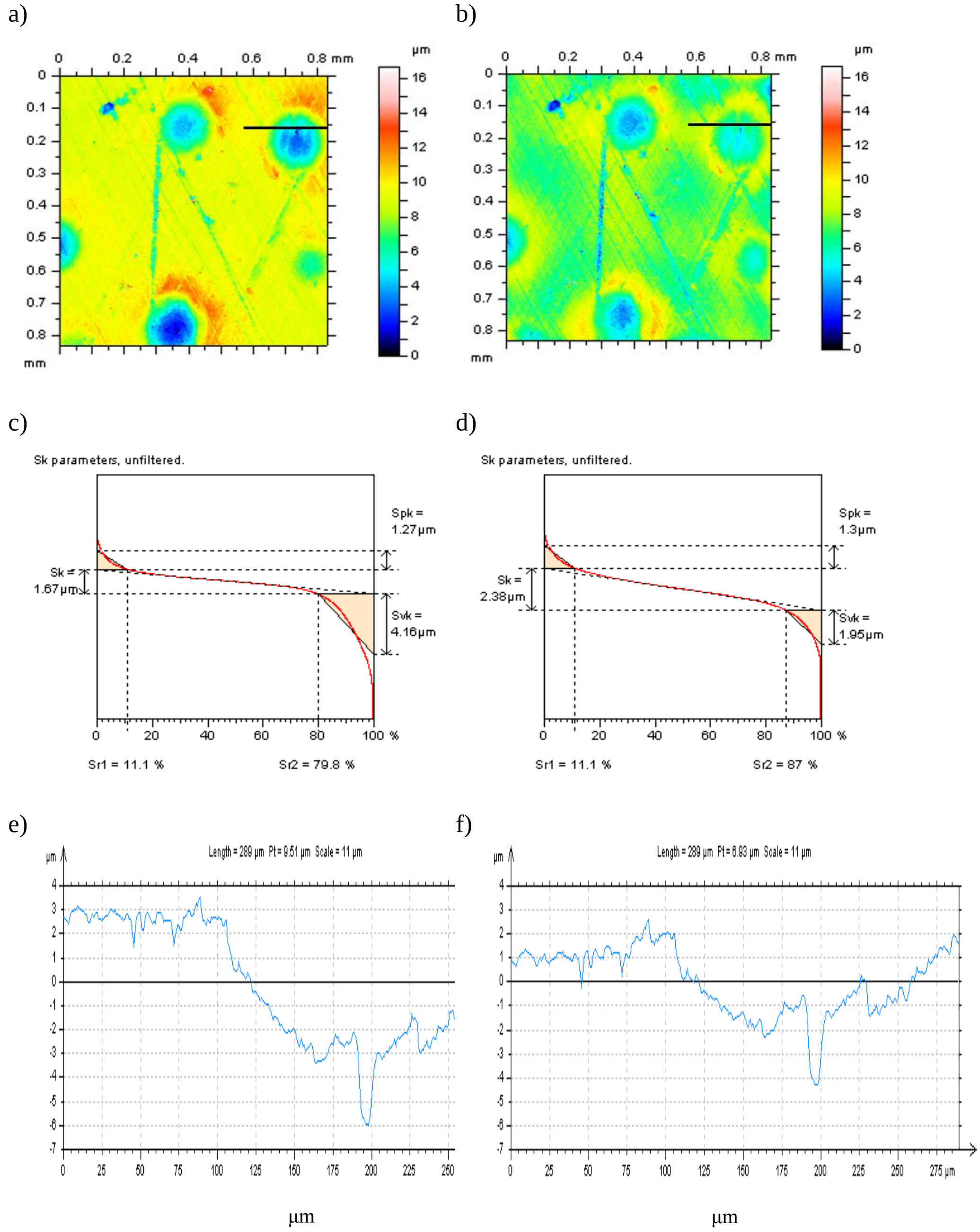


Fig. 2. Surface contour plots (a, b), material ratio curves (c, d) and shapes of dimple (e, f) of plateau honed cylinder surface with additional oil pockets created by burnishing method after form removal by degree of a polynomial: 2 (a, c, e) and 8 (b, d, f).

Generally, for a textured surface with separated oil pockets it was found that when the polynomial degree was higher than 2 or 3, areal surface parameters could be improperly calculated and, more importantly, the dimple depth and the oil capacity could be underestimated, the *Sk* parameter overestimated and therefore, the tribological properties of the analyzed assembly could be falsely assessed. For this surface type, a similar procedure is proposed to that of the plateau honed surface - computing parameters for the polynomial degree increasing and selection of this degree from which the parameter *Sk* (and *Sp*) started to increase. The analysis of the other parameters, like skewness *Ssk* and kurtosis *Sku* can also be helpful. Because textured cylinder surfaces with added burnished oil pocket are more susceptible to errors due to improper selection of the reference plane compared with plateau-honed cylinder textures, the 2nd and 3rd degree of polynomial was recommended. The use of a cylinder did not allow to correct the form removal, the resulting statistical parameters *Sa* and *Sq* were too high. Similar results were obtained for textured cylinder surfaces after low wear.

3.3 Piston skirt surfaces

Piston skirt surfaces after machining (turning) are different from cylinder surfaces analyzed in the previous sections. They are deterministic one-process surfaces. After low wear these surfaces became two-process surfaces with negative skewness *Ssk*; however they did not contain deep valleys. Therefore it was expected that an increase of the degree of a polynomial would not cause distortion of surface topography measurement results.

When surfaces did not contain curvatures, application of polynomial of the 3rd or better 4-th degree led to proper form removal. When the polynomial degree increased, the height parameters decreased; the spatial parameters *Str* and *Sal* had a tendency to decrease, but *Spd* to increase. *Sdq* and *Sdr* are parameters of small changes on the piston skirt surface depending on the reference element. The *Std* parameter was constant. It is necessary to state that use of a higher degree of the polynomial caused small changes of parameters, not serious distortion was found when the degree of the polynomial was high, therefore presumptions were confirmed.

Table 2. Parameters of the piston skirt surface for various reference planes.

Parameters	Cylinder	Polynomial of 2nd degree	Polynomial of 3rd degree	Polynomial of 4th degree	Polynomial of 6th degree	Polynomial of 8th degree	Polynomial of 10th degree	Polynomial of 12th degree
Sq, μm	8.97	3.43	1.81	1.06	0.75	0.75	0.74	0.74
Ssk	0.16	-1.09	-0.85	-0.52	-0.79	-0.78	-0.79	-0.78
Sku	2.54	6.07	5.21	3.86	4.31	4.25	4.35	4.29
Sp, μm	27.5	7.01	4.43	4.19	3.51	3.51	3.38	3.38
Sv, μm	21.31	17.31	9.78	5.91	6.38	6.23	6.36	6.31
Sz, μm	48.8	24.3	14.2	10.1	9.9	9.7	9.7	9.7
Sa, μm	7.29	2.64	1.41	0.83	0.61	0.61	0.59	0.59
Sal, mm	0.5231	0.1561	0.1661	0.0946	0.0522	0.0522	0.0522	0.0522
Str	0.532	0.156	0.169	0.232	0.054	0.054	0.069	0.069
Std, °	0.331	0.333	0.333	0.332	0.333	0.334	0.334	0.333
Sdq	0.0942	0.0936	0.0903	0.0886	0.0879	0.0878	0.0877	0.0877
Sdr, %	0.442	0.436	0.406	0.391	0.384	0.384	0.383	0.383
Spd 1/mm^2	0.5	8.8	57.5	139.1	152.1	153.1	161.1	167.1
Spc 1/mm	0.0179	0.0341	0.0315	0.0295	0.0292	0.0292	0.0291	0.029
Sk, μm	24.21	7.56	4.73	2.63	1.81	1.81	1.81	1.79
Spk, μm	7.93	1.67	1.15	0.65	0.34	0.32	0.29	0.29
Svk, μm	5.37	8.94	3.04	1.34	0.98	0.98	0.98	0.97
Sr2, %	90.1	93.8	92.1	88.3	84.1	84.2	85.1	84.8

The use of the cylinder as the reference plane did not allow to correct form removal from piston skirt surfaces. It is evident from the analysis of surface isometric views; the height parameters were too high. This observation was confirmed with regard to cylinder surfaces. Bad form elimination may be caused by errors in the commercial computer software used; the present authors found that their original procedure led to better form removal by cylinder as the reference element.

When the surface contained curvatures, application of polynomial of the 3rd and 4th degree did not lead to proper form removal. It was found that in this case application of a polynomial of the 6th or the 8th degree was required. For further increase of the polynomial degree, small changes of parameters were observed. Table 2 presents selected parameters of a piston skirt surface containing curvature. The height parameters *Sq*, *Sp*, *Sv*, *Sz*, *Sa*, *Sk*, *Spk*, *Svk*, kurtosis *Sku*, spatial parameters *Sal* and *Str* as well as material ratio *Sr2* decreased, but skewness *Ssk* and peak density Spd increased during an increase of the polynomial degree, the hybrid parameters *Sdq*, *Sdr* as well as peak curvature *Spc* also decreased, but their changes were smaller.

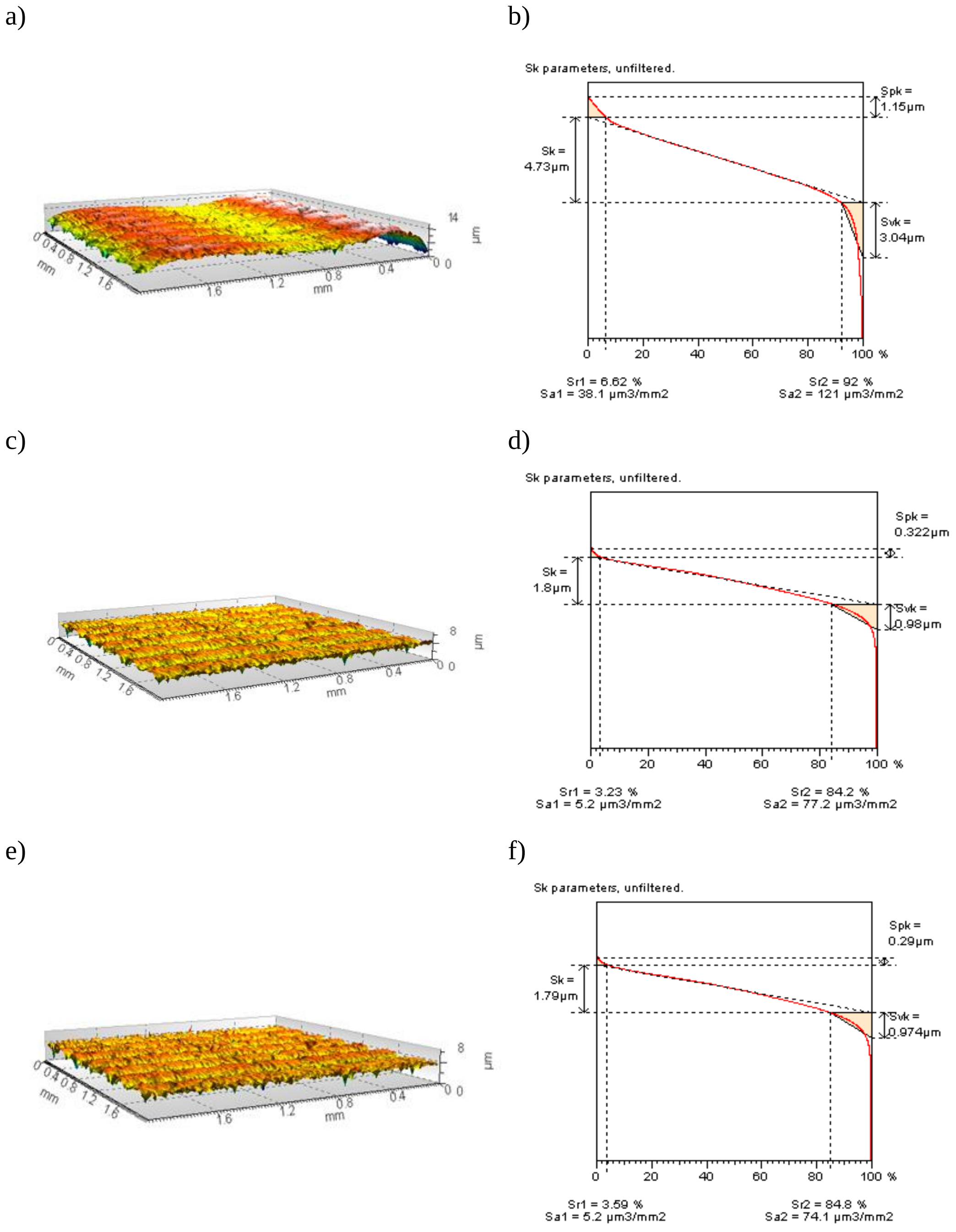


Fig. 3. Surface contour plots (a, c, e) and material ratio curves (b, d, f) of worn piston skirt surface after form removal by a degree of polynomial: 3 (a, b), 8 (c, d) and 12 (e, f).

However, further increase of the polynomial degree above 6 did not cause significant changes of parameters. Figure 3 presents contour plots and material ratio curves, when form was removed by polynomials of 3rd, 8th and 12th degrees. It is evident that application of a polynomial of the 8th degree led to elimination of curvature. It is suggested to find the reference plane for this type of surface by selecting this polynomial degree for which the changes of parameters will be small during further increase of the degree. Generally, when the surface does not contain curvatures, a polynomial of the 3th or 4^{th} degree is recommended, for surfaces with curvature polynomials of the 6^{th} – 8^{th} degrees are proposed.

The problem can arise for two-process surfaces with deep and wide valleys containing curvatures. A special procedure should be developed for form removal.

One can see from the presented analysis that serious errors in parameter calculations can be caused by improper selection of the reference element. For functional textures, form elimination seems to be a better alternative to digital filtration.

4. Conclusions

1. Improper selection of the reference plane can cause distortion of surface topography measurement results. Multi-process (stratified) surfaces of asymmetric height distribution are susceptible to errors connected with selection of the reference plane.

2. Application of a cylinder as the reference element did not lead to proper form removal of cylinder liners and piston skirts surfaces. Application of a polynomial gave better results, it is recommended to increase the degree of a polynomial and analyze changes of surface topography parameters in selection of the reference element. It is possible to increase the accuracy of form elimination by cylinder using an improved program compared with commercial software.

3. For plateau honed cylinders the 3^{rd} or 4^{th} degree of polynomial is suggested as reference element. Further increase of the degree of a polynomial can cause false estimation of surface topography parameters, like *Sk*, *Sp*, *Spq*, *Ssk* or *Svk*. The possibility of errors is higher when the width and depth of honing valleys are higher. It is necessary to choose the degree from which the *Sk* and *Sp* parameters started to increase when the polynomial degree increased.

4. Similar changes of parameters were found for plateau honed cylinders containing additional burnished dimples. Selection of the degree of the polynomial should be similar to that for a plateau honed cylinder surface. Because the changes of parameters are bigger than those of plateau-honed cylinders (as a result of larger dimple width) it is suggested to use a polynomial of the 2^{nd} or 3^{rd} degree. Changes of parameters with an increase of the degree of a polynomial are connected with a decrease of oil pocket depth.

5. When the piston skirt surfaces contain curvatures, the application of a polynomial of the 6^{th}-8^{th} degree is recommended. In other cases, the 3^{rd} or 4^{th} level is suggested. An increase of the degree of a polynomial does not cause serious errors of surface parameter estimation.

6. The increase of the degree of a polynomial causes a decrease in amplitude parameters and spatial parameters *Sal* and *Str*. The peak density *Spd* has a tendency to increase. Change of the reference plane causes small changes of hybrid parameters *Sdq* and *Sdr*. The *Std* parameter is constant on the surface independently of the reference plane used.

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