PISTON RING TOPOGRAPHY VARIATION AND ROBUST CHARACTERIZATION

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Abstract: In this paper, the surfaces of the two lands of twin oil control ring were investigated, since they play the key role in controlling the desired low emission and fuel levels designed for modern internal combustion engines. The goal is to map the variation in surface roughness of piston rings that appear at different scales from form and waviness to micro and nano roughness. Areal topography measurements were made by white light interferometer designed at the Halmstad University able to measure and scan the total functional area of the set of commercial piston rings. The results show both the variation and uncertainty of ring topography. The most stable parameters were found and recommended for an effective quality control.

Keywords: piston ring, white light interferometer, surface topography, measurement uncertainty.

1. INTRODUCTION

Stricter emission standards put more pressure on development and production of engines with lower fuel consumption and lower emission (DieselNet). For the successful cylinder kit construction good control over cylinder liner and piston rings assembly surfaces are required. A recent study by Holmberg et. al.(2011) showed that the piston assembly is responsible for significant amount of the engine friction losses in passenger cars. Piston rings form a piston pack in combustion engine that usually consist of 3-5 rings. The main function of oil control ring is to control the thickness of oil film between ring pack and liner surfaces. The flexibility of the piston ring is designed to compensate for longer wavelength deviations of the mating cylinder liner surface. Therefore it is important to obtain micro geometry surfaces with good functionalities for the ring/liner contact. Today surface quality control of the piston rings surfaces shows a lack of information to predict the functionality of the rings produced, because mainly only 2D measurements are used. The topography variation exist in global and local scale, and need to be mapped for getting a better understanding of influence of surface roughness and waviness on friction losses in engine.

This paper present the global and local variations in oil control piston rings roughness by using a white light interferometer designed at Halmstad University adapted to measure and scan selected area of a piston ring of heavy duty truck engines.

2. MATERIALS AND METHODS

2.1. *Piston rings*

Twelve twin land oil control rings of heavy duty truck engines, which consist of two narrow lands from three different batches, were investigated. 24 measurements evenly distributed over the surface with 15 degree intervals were made in circumferential direction on each ring land (Figure 1).

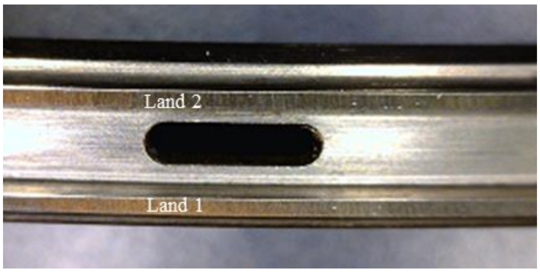

Fig. 1. View of twin oil control ring used in experiment.

2.2. Measuring equipment

For this experiment optical 3D measuring instrument designed at Halmstad University is used. The instrument is a white light interferometer (WLI). Figure 2 demonstrates general view and description of main components of the instrument. This type of technique is a leading optical technique for measurement of engineering surfaces. The advantage of WLI is its ability to scan the whole area, not point by point scanning (Malacara 2007). A 10x Mirau-objective was used in WLI. The camera is based on a CCD sensor with 2456x2058 pixel resolution. Piezoelectric motor with 100µm scan range and 0,7nm scan resolution is built in WLI. The measuring area of WLI is 880µm*660µm with 359x350nm lateral resolution and the vertical resolution applied in experiment was 5nm.

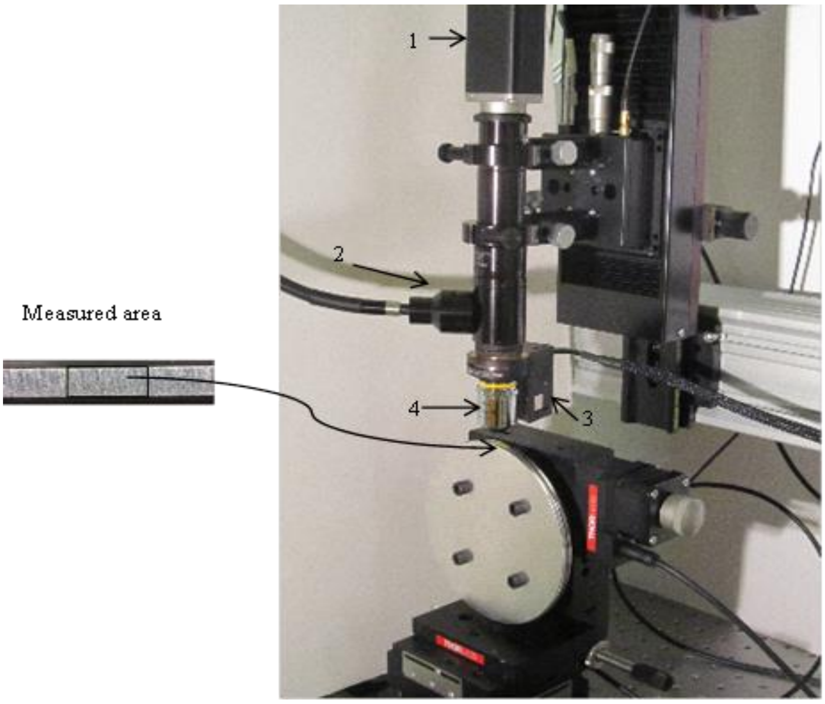

Fig. 2. White Light Interferometer (WLI). Description: 1-CCD camera, 2- white light source, 3-piezomotor, 4-Mirau-objective.

2.3. Complementary measuring technique

For a reference, additional measurements were performed on a commercial interferometer MicroXam (KLA-Tencor Corporation). The measuring area is approximately 613.96µm*808.12µm (1.287µm by 1.089µm lateral resolution).

To ensure the quality of measurement, comparison measurements were made on reference surface type C1 (ISO 5436-1:2000) fabricate Halle fabr.-nr.:1087289 2464 PTB 87 and 1.
MountainsMap® Premium 7.0 (Digital-surf) software was used for pre-processing and calculation of profile and area parameters.

2.4. Surface texture parameters used in study

In this study profile parameters: Ra-Arithmetic mean deviation of the assessed profile; Rz-Maximum height of the profile within a sampling length and Rt-Total height of the profile on the evaluation length, according to ISO 4287-1997 were used.
Areal parameters according to ISO 25178-2:2012: Sa- Arithmetical mean height; Sq- Root mean square height; Sk- Kernel roughness depth; Spk- Reduced peak height; Svk- Reduced valley depth; Str- Texture-aspect ratio; Std- Texture direction; Spd- Density of peaks; Spc- Arithmetic mean peak curvature; S10z- Ten point height - for surface investigation were used.

3. RESULT AND DISCUSSIONS

In this section a validation of the new constructed instrument (WLI) is performed. For the validation, comparison between a commercial instrument and the new designed instrument were used, after measurements of piston rings were performed by WLI. The suitable parameters for surface characterisation with measurements uncertainty were calculated afterwards.

3.1. Comparison between MicroXam interferometer and WLI designed at Halmstad University.

Measurement on reference surface. Comparisons were performed both between profile and areal parameters.
Areal measurements were performed by MicroXam and WLI interferometers on reference surface Halle. Using MountainsMap® Premium 7.0 three profiles were extracted from areal measurements, the average value of Ra, Rz and Rt parameters were compared, the Robust Gaussian filter and cut-off 800µm were used (ISO 16610.21:2011).

Table 1. Profile parameters calculated from measurement on reference surface by two instruments.

	WLI (optical)	**MicroXam (optical)**	**Calibrated value (stylus)**
Rz (µm)	1,75	1,54	1,31±0,04
Rt (µm)	1,95	1,54	1,69±0,08
Ra (µm)	0,214	0,218	0,181±0,005

Calculated value obtained as result of measurements by stylus profilometer and difference between calibrated value and value obtained by both optical instruments could be due to the stylus tip radii, restricting the mecanical probe to resolve the finest features on the reference surface (see Table 1). Variation in value of Rz and Rt between WLI and MicroXam is result of the different resolution and existence of non-measured points in MicroXam measurement.

For the comparison of areal parameters the same parameters that were used for the further investigation of piston rings were chosen. The measurements were filtered by Robust Gaussian filter with cut-off of 80µm, after the leveling by least square method (ISO 25178-2:2012).

Result shown at Figure 3 and Table 2 displays the result of comparison. Difference in height and functional parameters value can be explained by different resolution of instrument. Value of feature parameters should be interpreted with care. Pixel size of the newly constructed WLI is 0,359x0,322 µm while the MicroXam have lower 1.089µm by 1.287µm which has sufficient influence on calculation of those parameters (Thomas 1999). However it was chosen to present and discus this difference in paper considering the importance of feature parameters for testing and simulation processes in tribology.

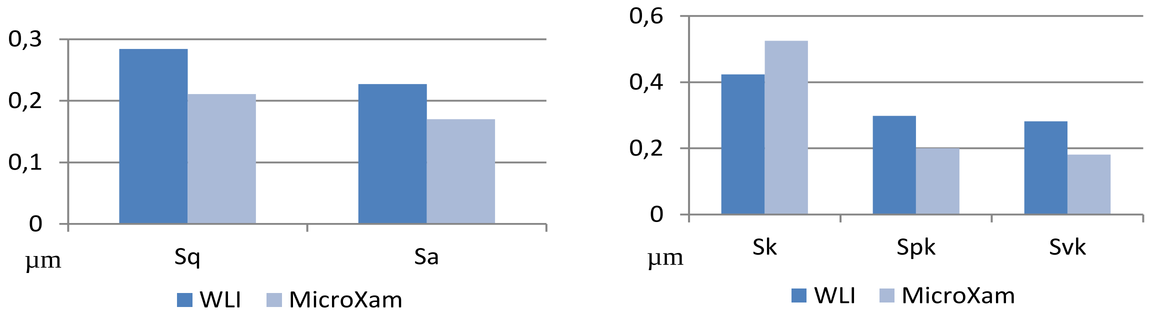

Fig. 3. Height and functional parameters calculated from measurement on reference surface performed by WLI and MicroXam.

Table 2. Result of area parameters value.

	WLI	**MicroXam**
Feature Parameters		
Spd (1/µm²)	0,050	0,002
Spc (1/µm)	4,635	0,176
S10z (µm)	2,605	1,36

	WLI	**MicroXam**
Spatial Parameters		
Str	0,077	0,012
Std (°)	89,5	89,5

Measurement on piston rings. Comparison between two instruments was made by using the piston ring surface. Four measurements were performed on the piston ring surface. Relocated area was measured by MicroXam interferometer and WLI. Once the surfaces acquired, the following pre-processing is performed by using MountainsMap®: the form was removed by fitting 4th order polynomial and subtracting it from the surface data. Afterwards the Robust Gaussian filter (cut-off 25µm) was used to separate the waviness and roughness, no noise reduction using λs was made. Figure 4 displays the height and functional parameters and their standard deviation.

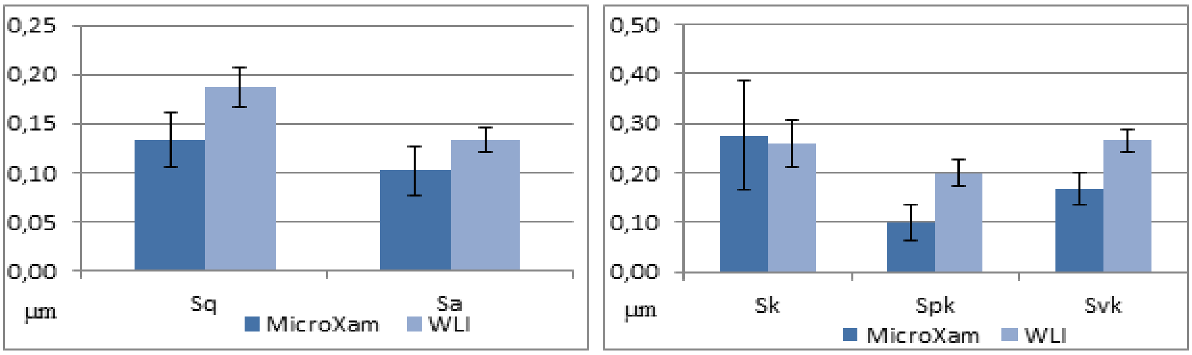

Fig 4. Height and functional parameters of piston ring surfaces after form removal.

Variation of standard deviation of WLI is lower than for MicroXam measurements, showing good repeatability of the WLI. Measurement uncertainty for Sq, Sa, Sk, Spk, Svk is estimated to ±30nm.The specified uncertainty is the product of the standard uncertainty of measurement multiplied by the coverage factor k = 2, which for a normal distribution corresponds to a coverage probability of approximately 95%. The measurement uncertainty has been determined in accordance to GUM (JCGM 100:2008).

The same trend regarding feature parameters has been observed in comparison between two instruments when measurements on piston ring were performed (see Table 3). By including spatial parameters in comparison the anisotropic characteristic of surface (Str near 0), and angle of main direction of surface (Std) were compared. Results from Table 3 indicate large variation for feature parameters probably caused by the mentioned difference in lateral resolution.

Table 3. Result of area parameters value after form removal.

	WLI	MicroXam
Feature Parameters		
Spd (1/µm²)	0,024	0,005
Spc (1/µm)	4,835	0,142
S10z (µm)	2,358	1,160

	WLI	MicroXam
Spatial Parameters		
Str	0,086	0,056
Std (°)	97,5	96,6

Examination of waviness parameters calculated from measurement acquired by two instruments shows no significant difference (see Table 4). Indeed they show a high correlation and confirming the two instruments comparability for longer wavelenghts.

Table 4. Result of waviness parameters value.

	WLI	MicroXam
Height Parameters		
Sq (µm)	0,052	0,050
Sa (µm)	0,041	0,039
Functional Parameters (Stratified surfaces)		
Sk (µm)	0,072	0,079
Spk (µm)	0,035	0,032
Svk (µm)	0,051	0,053

	WLI	MicroXam
Spatial Parameters		
Str	0,196	0,138
Std (°)	100,3	98,9
Feature Parameters		
Spd (1/µm²)	0,0003	0,0003
Spc (1/µm)	0,002	0,002
S10z (µm)	0,217	0,210

Roughness parameter presented in Table 5 shows the same trend as parameter after form removal presented in Figure 4 and Table 3.

Table 5. Result of roughness parameters value.

	WLI	MicroXam
Height Parameters		
Sq (µm)	0,178	0,116
Sa (µm)	0,119	0,084
Functional Parameters (Stratified surfaces)		
Sk (µm)	0,205	0,225
Spk (µm)	0,207	0,105
Svk (µm)	0,273	0,165

	WLI	MicroXam
Spatial Parameters		
Str	0,096	0,055
Std (°)	97,5	96,6
Feature Parameters		
Spd (1/µm²)	0,025	0,006
Spc (1/µm)	4,793	0,138
S10z (µm)	2,375	1,190

3.2. Surface topography characterization of the piston rings

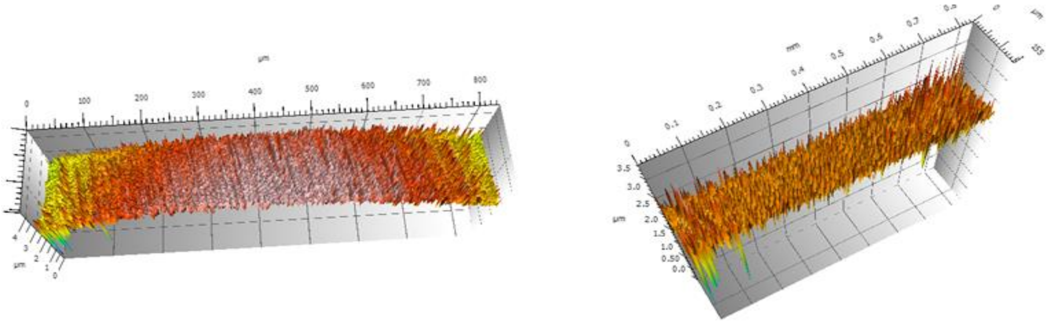

Fig.5. Example of a piston ring surface obtained before and after the pre-processing.

Measurements were made on 12 twin land oil control piston rings with two lands from three different batches. A wide range of surface parameters were computed from the pre-processed surface (see Figure 5) and includes the main families: height, spatial, functional and feature parameters.

Figure 6 shows variation of Sq value of surfaces after form removal over all the rings at both lands. It was observed variation of Sq parameter in range of 0,11-0,15µm for batch1, in range of 0,18-0,20µm for batch 2, and in range 0,14-0,22µm for batch 3, also Sa, Sk, Spk, Svk showed similar trend as Sq concerning the ability to separate total population into at least two groups: batch 1 and batch 2 + batch 3. Result and reasoning on Sq parameter became the basis for further investigation of other parameters of the same batch. Result of variation of Sq, Sa, S10z, Sk, Svk and Spk parameter can be seen in the Figure 7.

The example of results of height and functional parameters is presented in the graphic form in figure 7. In all the graphs the line inside the frame box represents the median value; the frame box represents the range from percentile 25% (first quartile) to percentile 75% (third quartile) and the whiskers show max and min value of the parameter.

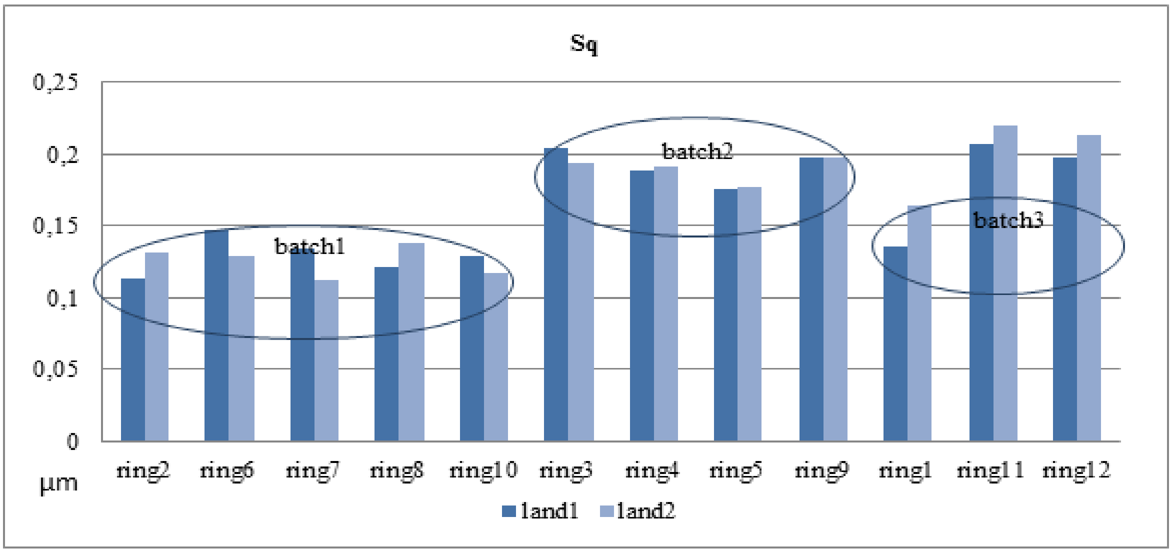

Fig 6. Mean value of Sq parameter from 24 measurements made in circumferential direction on each ring land.

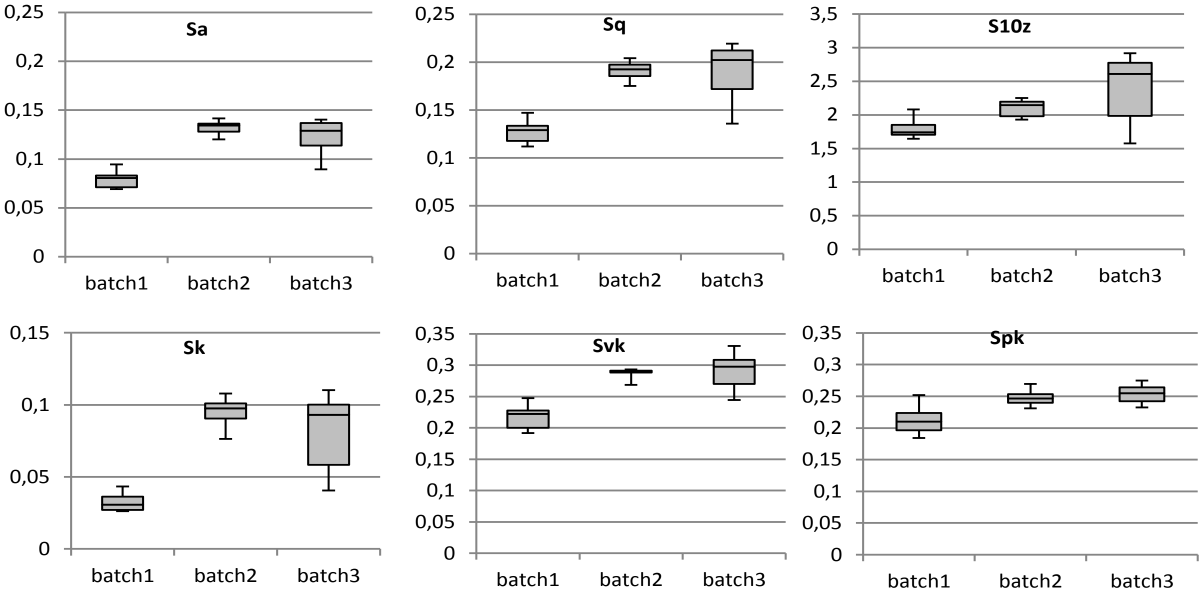

Fig 7. Variations of the height and functional parameters according to each batch.

Table 6. Result of area parameters value.

	batch1	batch2	batch3
Spatial Parameters			
Str	0,149	0,159	0,155
Std (°)	97,0	99,5	100,8
Feature Parameters			
Spd (1/mm²)	4674	5833	8042
Spc (1/mm)	722	910	2457
S10z (µm)	1,790	2,104	2,388

Examination of all parameters presented in Figure 7 shows the highest variation of parameters value in batch 3 and lowest variation observed in batch2. It was remarked that the value of all parameters were lowest for all the rings in batch 1. Median value of Sa e.g. for batch 1 was 0,081µm compared to 0,134µm for batch 2, and 0,129µm for batch3. It is obvious that piston rings from batch 1 have the smoothest surface. Parameters from Figure 7 are recommended for production control. During measurements of piston rings it was found that the width of the examined areas varied, but further investigations to find the correlation between the variation in land width and surface properties need to be made.

Str parameter (see Table 6) is used to identify texture pattern indicates stronger long-crestness texture aspects (Str<0,3), while Std –used to determinate the pronounced direction of the surface texture with respect to y-axis gives the lay direction of the surface. Examination of the measured surfaces shows that the positive angle is approximately 100 degree.

As observed from Figure 8 and Table 7 waviness of surfaces for piston rings lays in nanometer level and variation of all parameters are highest for batch 3. Parameter Sk varied in range 1-3 nm for batch 1, for batch 2 in range 0-1 nm, for batch 3 in range 0-4 nm. As it can be seen in Figure 8, the waviness of batch 3, the difference can be more than 10% between lands of the same rings and between rings.

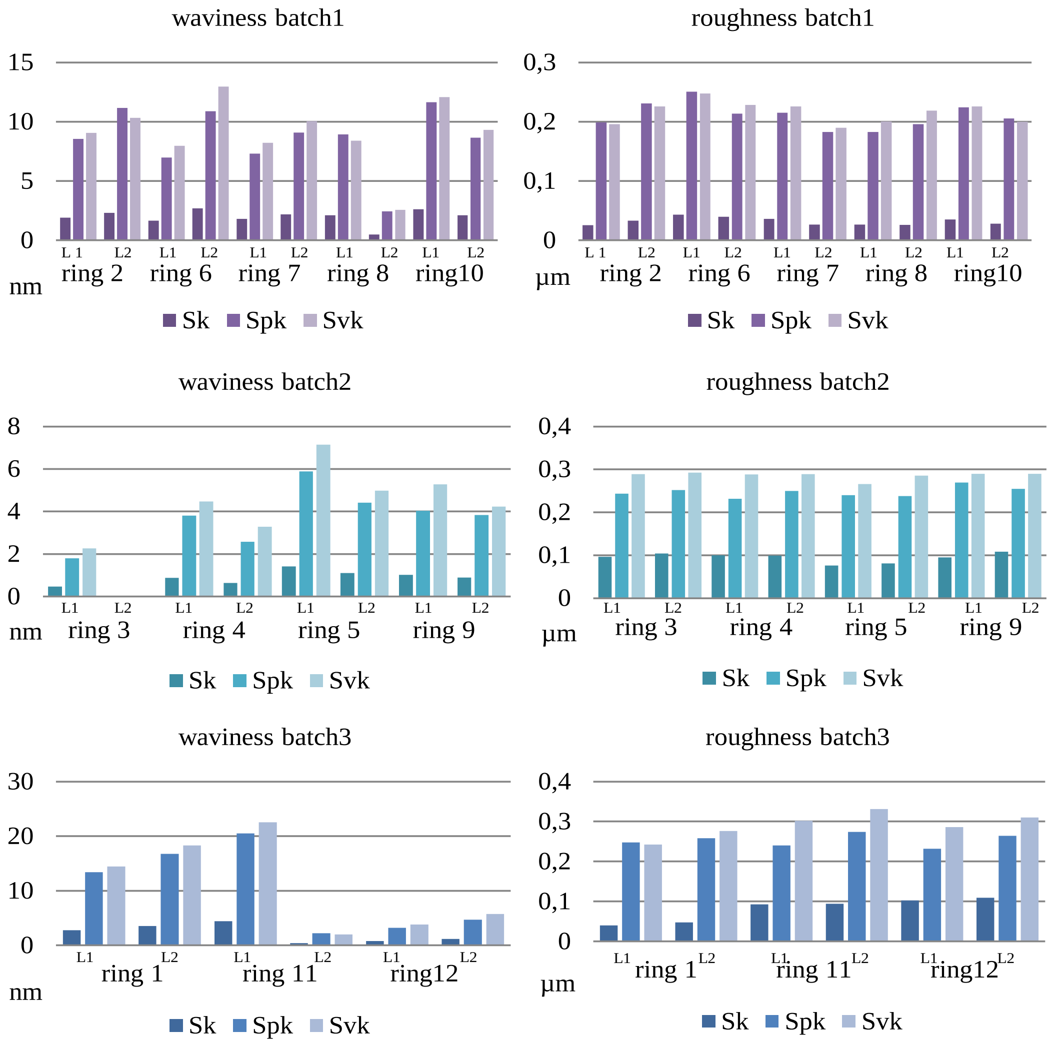

Fig. 8. Waviness and roughness parameters presented for each land of each ring.

Roughness parameters demonstrated at the Figure 8 and Table 7 show higher variation of all the parameters for batch 3 compared to batch 1, and batch 2. Feature parameters Spd and Spc define summits density and average of the principal curvatures of summits within the sampling area. Those parameters have nearly same value as the parameters after form removal. As it can be seen the filtering has no effect on the trend and stability of parameters. For a simple quality control, no filtering need to be used for examination of piston rings surfaces; only a form removal is recommended to see the same trends.

Table 7. Result of waviness (left) and roughness (right) parameters.

	batch1	**batch2**	**batch3**
Height Parameters			
Sq (nm)	30,1	11,2	28,5
Sa (nm)	23,6	8,9	21,3
Spatial Parameters			
Str	0,250	0,340	0,242
Std (°)	87	100	97
Feature Parameters			
Spd (1/mm²)	189,53	270,71	198,91
Spc (1/mm)	0,70	1,73	1,38
S10z (nm)	96,6	41,8	99,7

	batch1	**batch2**	**batch3**
Height Parameters			
Sq (µm)	0,123	0,176	0,178
Sa (µm)	0,067	0,112	0,104
Spatial Parameters			
Str	0,159	0,161	0,179
Std (°)	97	99	101
Feature Parameters			
Spd (1/mm²)	4833	6138	7995
Spc (1/mm)	711	918	2461
S10z (µm)	1,797	2,116	2,418

4. CONCLUSIONS

Validation of the WLI designed at the Halmstad University was performed. The following was found:

a) Instrument can be used for investigation of other types of surfaces, impossible to measure by the commercial interferometer (MicroXam).
b) Instrument shows good repeatability of the height and functional parameters.

In future, the instrument behavior in lower and higher range can be studied.

In this paper the set of parameters from different families were proposed for characterization and production control of surface topography of the twin land oil piston rings. Experimental results have been provided to demonstrate the effectiveness of chosen parameters. From the measurements done with the WLI build at the Halmstad University, the following conclusions were found:

c) The robust parameters for characterization of piston ring surfaces are Sa, Sq, Sk Spk, Svk, Str,Std.
d) Measurement uncertainties of those parameters are estimated to ±30nm.
e) Feature parameters Spc, Spd, S_{10z} analyzed in the paper require further considerations because of their sensitiveness to sampling interval adopted in measuring surface topography.
f) For a simple quality control, the same trends could be seen without filtering
g) Variation of chosen parameters both within batch and between rings was un-expectantly high.

In the future, result of this study can be used as input to simulation and testing processes for investigation of friction and friction variation, correlating the tribological properties to robust surface parameters. Variation of ring form/waviness/roughness have an important influence on the piston ring function and they all should be further investigated.

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