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CYLINDER LINERS AND CONSEQUENCES OF IMPROVED HONING

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Abstract

The demands on decreased environmental impact from vehicles are resulting in a strong push for decreased engine oil and fuel consumption. Engine oil and fuel consumption are to a great extend controlled by the topography of the cylinder liner surface.

Recent engine tests have shown a promising reduction in oil consumption when using cylinder liners with a smoother finish than the current plateau honing.
One approach to produce smoother liner surfaces is to replace SiC ceramic honing stones with diamond tools. However, event though the diamond honing process results in higher productivity, improved demands of quality control is needed to monitor the degree of cold worked material - "blechmantel" (*German*), and the resulting risk of increased wear and scuffing.
A number of petrol and diesel engine cylinder liners have been mapped to be able to verify the quality and consequences, in terms of wear and function, of the honing process. A new mapping method, combining SEM images and quantitative image analysis with traditional 2D profilometry has been developed and tested in this study. The liners where tested in a reciprocating rig of 8 mm stroke and with a frequency of 10 Hz, simulating the top-dead center conditions in a running engine.
The tests where carried out in high- and low pressure conditions with smooth respectively rough liner roughnesses against PVD coated piston rings. The developed surface mapping method was employed before and after the test to study effect of running-in wear on the surface, features characterized with the SEM- and the 2D profilometer.
The results show that combining SEM- and profilometric methods gives a good picture of the effects of varying the cylinder liner pressure and roughness. The core roughness decrease more for diesel liners than for petrol liners. In average (rough and smooth liners) the diesel core roughness decrease 265% while the petrol liners average on a 60% decrease. Blechmantel- and Irregularities ratio show a high sensitivity to varying conditions and decrease 1180% to 100% for the diesel liners while the parameters increase between 106% to 18% for all the petrol liners. A probable cause is the more severe diesel high pressure run-in conditions are able to effectively "truncate" the plateaux and remove residing plastically deformed un-cut honing residues while the less severe petrol liner conditions not manage to remove the blechmantel and irregularities in an important extent.

Introduction

The mechanical power loss in the engine accounts for about 15% of the total energy losses in the engine and half of this loss is caused by friction in the piston-liner system [1]. The interest is great from customers, society and manufacturers to further get to know and control the friction response and to optimise the manufacturing processes.

Besides friction, the oil consumption with unwanted of combustion products such as HC-, CO-, CO_2, NOx gas and particles emission can be controlled by the liner surface topography. [2].
A number of different engineering solutions exist and traditional honed grey cast iron engine blocks with steel piston rings have been replaced by lighter and more easily machined alumina engine block concepts. Still, the grey cast iron liner material is commonly used as the functional surface against the sliding piston ring contact.

The influence of the topography of the liner surfaces has been reported by Blunt et. Al. [3], Robota and Schwein [4] and others.

The finishing of the cylinder liner surface results in a criss-cross patterned topography consisting of a series of honing valleys of different density, peak radii, depths and widths related to selected machining parameters (speed, feed and surface pressure) along with selection of honing tool composition of grain size, grain material (diamond or SiC), binding material and grain density [5].

The term –*Gleithonung* [4] has been introduced, for liners characterised by plateaux with an amplitude range less than a third of the traditionally plateau honed liners, which in turn typically had plateaux with half the amplitude range compared to the liners not subjected to the plateau honing. The Gleithonung is based on traditional honing procedures and Diamond abrasive tools.

One approach to produce smoother liner surfaces is to replace SiC ceramic honing stones with diamond tools. However, event though the diamond honing process results in higher productivity, improved demands of quality control is needed to monitor the degree of cold worked material - "blechmantel" (*German*) (fig. 1), and the resulting risk of increased wear and scuffing.

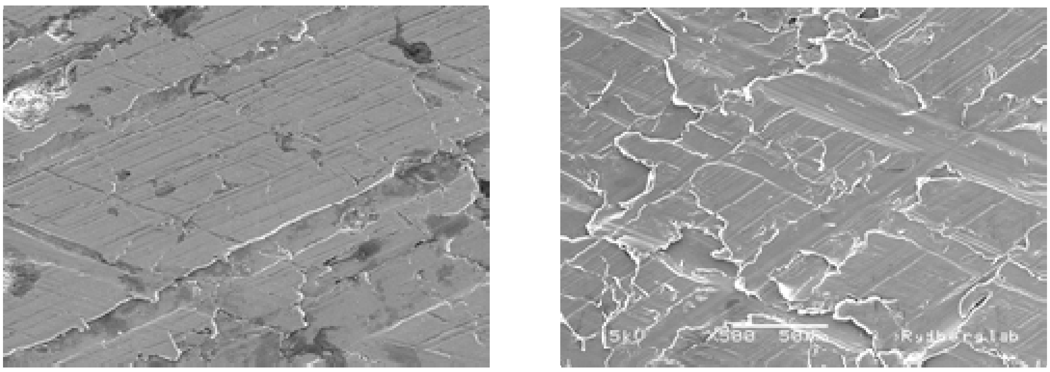

Fig. 1 SEM pictures of two cylinder liner surfaces with different degree of folded material, so called "blechmantel".

However, the amount of acceptable blechmantel is unknown. A comprehensive method to judge the degree of blechmantel is described in the GOETZE Honing Guide [6], and is based on roughness profile parameters, image analysis of SEM images of gold coated acetate replicas of cylinder liners, -faxfilm, and metallographic sections of the liner surface. SEM images are here visually compared with reference images. 2D profiles are evaluated manually or with roughness parameters and a rating, 0-10 (10 is excellent) is estimated depending on the weighting of five (5) non profiling properties (honing angle, orientation of grooves, plateau formation, groove appearance, macro waviness) and five (5) profiling properties (groove width (a), groove distance (d), grove height (C), bearing area at 2um (tp2), and micro waviness (Wt)) of the surface to an overall mean rating.

Beyer, Krahe and Leon [7] introduced an automated inspection method based on image analysis of SEM images. The honing structure where separated in background and honing groove structure using the Fast Fourier Transform FFT. The FFT and Radon transforms where then used to quantify background (holes, smearing, flakes) and groove features (groove interrupts, stray grooves, groove balance, groove shape, turning- and chatter marks). Additional profilometric quality criteria based on the ISO Ra, Rz, and Rmax as well as the Abbot curve (ISO 13565-2) where also proposed as a complement to the SEM analysis.

Several engine manufacturers has developed different methods based on the manual SEM analysis of the honing structures and in practice there exist a need for detailed and automated inspection, especially when new improved honing methods are being introduced. First, the scope of this study is to develop, implement and test a SEM image- and 2D stylus profilometry method combining the advantages of the Goetze and Beyerer approaches described above. Secondly, the aim is also to test the possibility to quantify effects on the surface structure by wear.

Material & Methods

Stylus Measuring device

The measuring device used in this study is a Surfascan 3CS[1]mechanical stylus system. The 3CS has a maximal horizontal range of 100*100 mm and a minimum horizontal (x,y) resolution of 2 μm. The vertical (z) resolution of the inductive laser linearised varying difference transformer probe, is 6 nm and the maximal vertical range is 6 mm. The horizontal resolution used for the 2D-measurements is 1 μm in x-direction using a 17.5 mm traversing length. The stylus used has a 2 μm radius and a 90 degree tip angle. The traversing speed used for the 2D measurements was 0.3 mm/s.

Scanning Electron Microscope -SEM

SEM images where produced by a the secondary electron detector of a JEOL[2] JSM-6490LV microscope with a maximum of 5nm lateral resolution.

Software

The software used for 2D profiles was the OmniSurf v1.67[3] and here the Surfascan type .smd files were imported directly to the OmniSurf software. Image analysis of SEM pictures where made using Matlab ™ [4] (v.7.1) and the Matlab Image Toolbox 5.1 software.

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[3] Digital Solutions Inc., USA, www.digitalsurf.com .
[4] The MathWorks Inc., USA, www.mathworks.com .

Measuring procedures

All profile measurements were preconditioned in the respective software by levelling against a least square line. Further, a form removal for 2D profiles by fitting and removing a 4'th degree polynomial to measured data was carried out. 2D- measurements were band pass filtered using cut-off wavelengths of 8 µm (ls) and 2.5 mm (lc) and the "robust Gaussian filter" by Bodschwinna et al. [3].
The 2D and 3D measurements were located to start 20 mm below the top of the liner with the positive x-axis direction (main measuring direction) of the measurements running co-linear with the cylindrical liners' centre line.

Liner types

The study investigated in total 8 different types of grey cast iron cylinder liners. The liners are centrifugally cast and inserted in injection mould alumina car engine blocks. The rough liner types are cylindrically honed using silicon carbides abrasives. The smooth ones are honed with diamond abrasives and represent the current commercial manufacturing concepts on two separated roughness levels.
Rough liners are "plateau honed" liners having rougher surface structure amplitude while smooth liners are manufactured under the same conditions using improved,
finer, plateau honing grit sizes than the rough type. The smooth honing liners represent the latest developments in commercial liner manufacturing and current state-of-the-art.
The different liner types where tested in a reciprocating rig of 8 mm stroke and with a frequency of 10 Hz [8], simulating conditions around the top-dead center in a running engine. Piston ring – cylinder liner pressure where selected according to true running values for petrol- (low pressure) and the diesel liners (high pressure) liners

Results and discussion

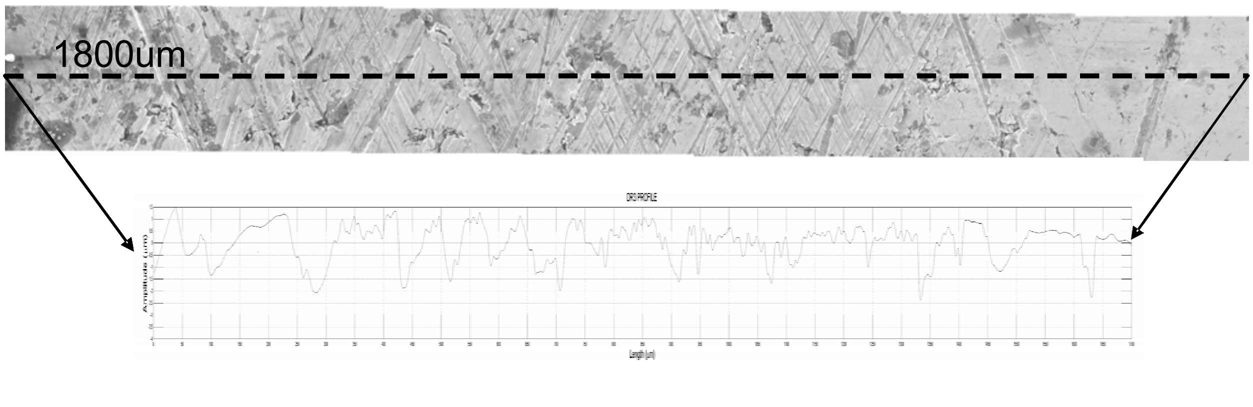


Fig. 2 Combining SEM images and profilometry

Characterisation method

To be able to analyse the result of the total honing process and to analyze changes in surface roughness, including "blechmantel", as a function of wear, eighth petrol and diesel liners have been tested. A new mapping method, combing SEM images and quantitative image analysis with traditional 2D profilometry has been developed and tested in this study. The image analysis take advantage of the high magnification and the possibility to extract 3D features not possible to easily extract from the 2D profiles measured by the stylus method.

Stylus profiles, however complete the SEM analysis with quantified measures of the “classic” profile features like profile heights and lateral measures.

Image analysis

In order to extract and quantify lateral features associated with the honing process image analysis is employed in order to utilize qualitative high magnificated SEM images. Ideally the honed structure consist of a plane, intersected by a manufactured criss-cross pattern of grooves resulting from the abrasive grits plowing trough the cylinder liner surface. The groove orientation is a result of the combined machining horizontal- and vertical cutting speeds. Groove distribution, width and depth is a result of honing tool grit density, size and pressure. The image analysis will therefore have the purpose to isolate and put numbers to expected and groove features like orientation as well as deviations from the perfect distributed groove pattern on the plane liner surface. The brightness and greyscale histogram distribution can vary from image to image due to deviations in measuring settings or differently tilted measuring objects. This calls for a preconditioning of the measurements using average filtering to remove slopes and greyscale averaging to make different images comparable on a more equal basis.

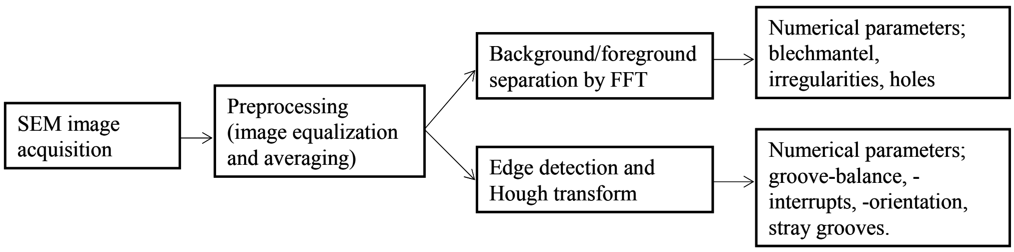


Fig.3. Workplan for the image analysis method

After pre-processing, background and foreground are separated by a Fast Fourier filtering where the groove components in a selected orientation are masked manually (fig. 3). When FFT filtering using the X-shaped mask, the inverse FFT transform of the filtered image recompose the background without the grooves’ components (Fig. 4).

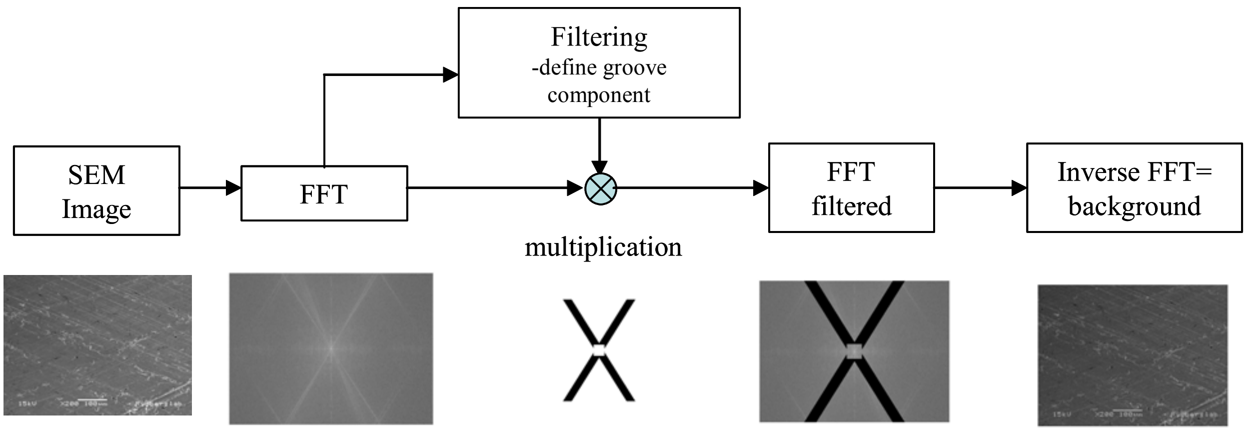


Fig. 4 The different steps followed for extracting the parameters blechmantel, irregularities and holes .

The inverse Fourier transform extracted background features consist of holes, blechmantel and irregularities. Blechmantel and irregularities are brightness intensity non-groove elements which size is larger respectively smaller than a set threshold. Holes are large low intensity areas in the image. Two kind of thresholds are then computed to differentiate those three features in the background : intensity threshold and size threshold.

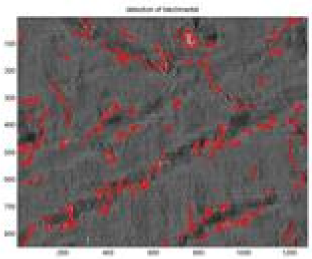
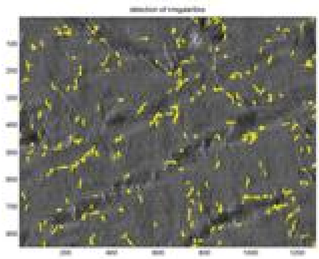
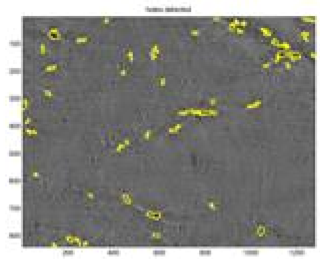
Extracted Background parameters (foreground/ groove structure removed)		
		
Blechmantel	*Irregularities*	*Holes*

Fig. 5 Background features extracted after FFT filtering and FFT inverse transformation for groove removal.

By employing edge detection to find distinct edges (valleys-, hole-, and blechmantel borders), linear features ie. grooves and groove sections, can be separated using the Hough-transform (eq 1):

$$\breve{g}(\rho,\theta) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} g(x,y)\delta(\rho - x\cos\theta - y\sin\theta)\, dx\, dy \qquad (1)$$

Here the main interest using this transform is to detect groove features in an image, where edges (groove and groove segments) can be expressed as grey level intensity in the original image position (x,y) as a function of distance from the centre point of the image in an orientation with the angle θ.

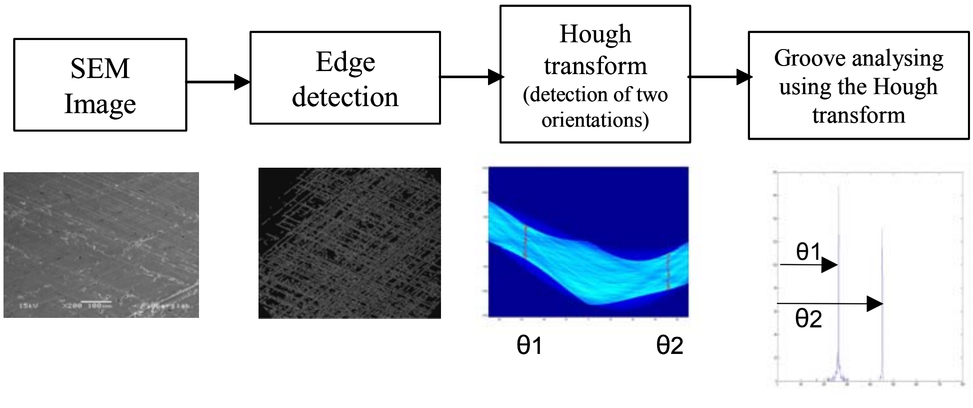


Fig. 6 By a combination of SEM imagining, classic edge detection, and analysis of the strongest parts of the Hough transform, dominant linear features as exemplified with the right most histogram at different θ-angles

Integration and thresholding in the different θ-angles enable quantification of orientations (stray and expected orientations), grove interrupts and balance (strength) between grooves in different angles. The groove orientation is naturally divided into left- and right hand grooves. By comparing the two groups, a groove balance can be calculated. Stray grooves are oriented in other orientations than the two main (left- right hand) directions whereas residual grooves are stray grooves with orientations similar to previous machining step directions, eg. turning marks not removed by the finishing plateau honing steps.

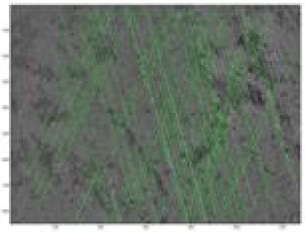
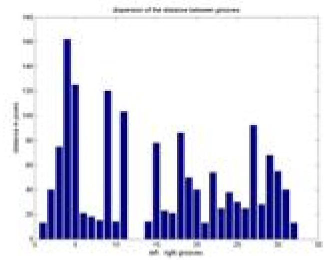
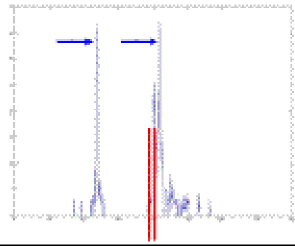
Groove parameters (extracted after edge detection and Hugh transform)		
		
Groove orientation	*Groove balance*	*Stray-and residual grooves*

Fig. 7 After groove detection (left), groove balance (mid) and distribution of groove orientations can be calculated from the histograms. The stray- and residual grooves (right) are oriented in direction other than the orientation of the two dominating (left-, righthand) orientations θ_1 and θ_2 in fig 5 above .

2D Profilometry

SEM image analysis need to be completed with the stylus profiling technique to provide quantitative depth information. Here, five (5) 2D parameters are used to quantify amplitude- and vertical properties of the grove components. Two of them are the standardized parameters: *Rmr* (percentage bearing ratio at depth of 1 µm and with the 5% highest peaks removed before calculation) and *Wt* (macrowaviness).

Additionally, three non-ISO standardized groove parameters are calculated: *the mean groove width (a)*, *the mean groove height* (C) and *the mean distance between grooves (d)*.
Grooves are defined as valleys deeper than the amplitude threshold c_2. c_2 need to be individually selected for each surface type and was choosen to 1um below the profile mean line in this study. Groove width is defined as the mean line distance between the two profile points constructed as the mean line crossing points when tracking the identified grooves' deepest points forwards, and backwards along the profile.

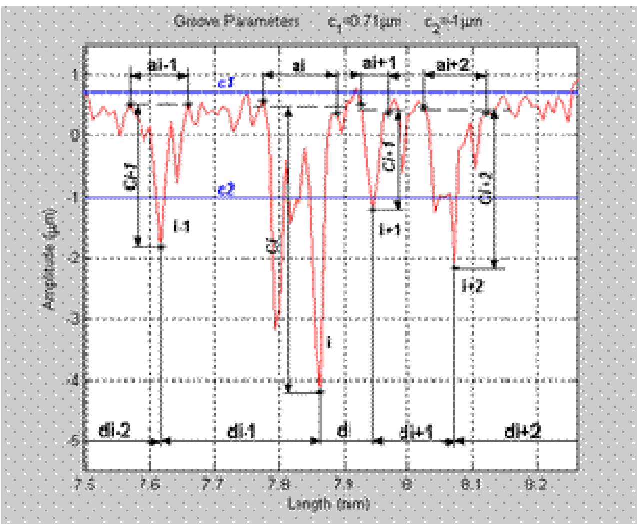


Fig. 8 Non-ISO standarized 2D profile parameters completing the SEM image analysis with groove characteristics.The three groove parameters here are; mean groove width (a), mean groove height(c) and mean distance between grooves (d).

Influence of SEM magnification on image analysis

The SEM has the advantage of a very broad range of possible magnifiction levels. For practical purposes, the image analysis method suggested above need to be performed on a magnification level chosen to result in parameters representative to the whole cylinder liner surface to be tested. To select appropriate magnifications, the same area where captured by the SEM at different magnifications to display the range and mean of the suggested image analysis parameters above.

For the honing groove orientation, groove balance, stray grooves, low magnifications, 50X-200X, promotes the capture of enough number of grooves to reach a low variation.

For the parameter group analyzing the details of the surface: blechmantel, irregularities, holes, groove interrupt, a compromise between a need of high magnifications to resolve details and the risks of getting too big dispersions between results with a too high magnification is needed (Fig. 8 below).

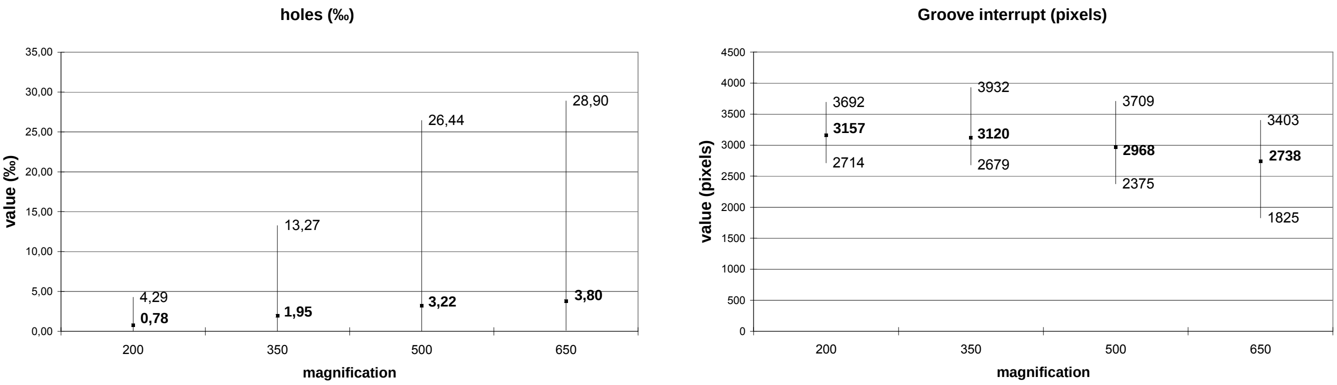


Fig.9 For 200X of magnification, holes and groove interrupt give a significantly smaller range of % holes than the larger magnifications tested. The grove interrupt parameter seems to be less sensitive to magnification chosen.

A low range is desirable when selecting the best magnification. For the different magnifications displayed in fig.xx above 200X magnification is selected due to the low ranges. In fig. 9 below, 500X magnification is selected for blechmantel and irregularities as a magnification where the mean stabilise compared to the next larger magnification 650X. Remaining image analysis parameters blechmantel and irregularities show a similar variation for the different magnifications tested.

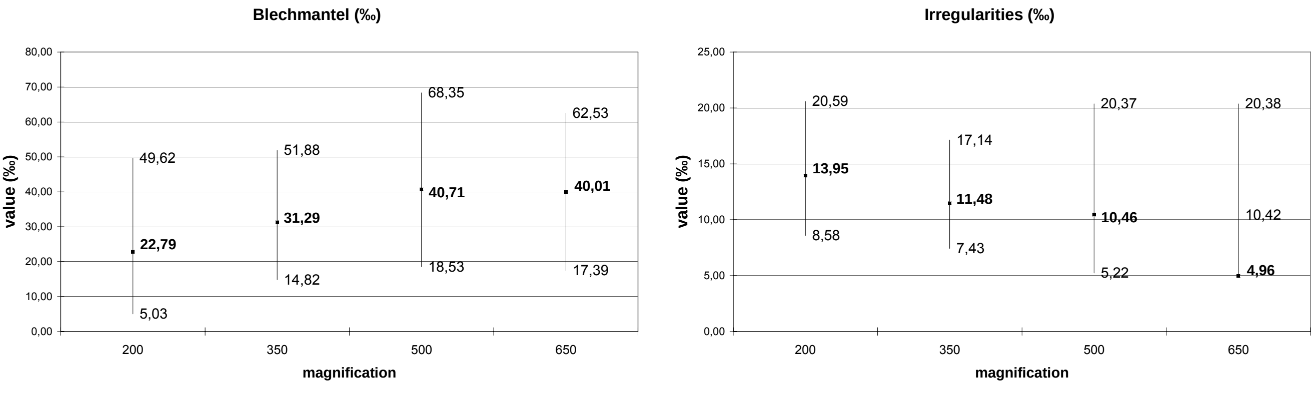


Fig. 10 Blechmantel- and irregularities parameters show a neglible sensitivity to magnification level in the SEM. Any magnification from 200X to 650X are possible to use for the analysis.

Quantification of the eight tested cylinder liners

Table 1 below display image-, peak- and valley-, ampliude-, and "other"- roughness parameters for worn and unworn diesel (high pressure) and petrol (low pressure) at two initial roughnesses (rough and smooth). The roughness parameters have been divided into type of parameters (amplitude, lateral) and class of parameters (peak, core and valley) to simplify the interpretation of the measurements by grouping into logical families.

Table 1

					DIESEL				PETROL			
					Rough		Smooth		Rough		Smooth	
	parameter	unit		magn.	unworn	worn	unworn	worn	unworn	worn	unworn	worn
IMAGE ANALYSIS	angle	deg.		200X	128,8	N/A	137,8	N/A	133	133	133,3	135,3
	orientation			200X	0,3	N/A	0,6	N/A	0,3	0,6	0,5	0,6
	balance	pixels		200X	79,1	N/A	38	N/A	71,9	46,5	36,7	37,6
	stray ratio	-		200X	0,1	N/A	0,1	N/A	0,8	0,2	0,3	0,1
	holes ratio	‰		200X	30	17	6	4	8	N/A	11	13
	"			500X	36	13	17	21	12	N/A	18	19
	blech ratio	‰		200X	21	8	27	7	3	16	14	7
	"			500X	64	5	34	9	17	35	28	37
	irregularities ratio	‰		200X	23	5	15	9	8	23	10	17
	"			500X	20	3	12	6	17	20	10	19
	groove interrupt	no. of pixels		200X	3160	N/A	2944	N/A	3515	3162	3283	3312
	"			500X	2633	N/A	2779	N/A	2988	2890	3022	3104
			type of parameter	class of parameter								
PEAK- and VALLEY PARAMETERS	Rpk	µm	amplitude	peak	0,44	0,21	0,33	0,14	0,33	0,25	0,26	0,14
	Rmr1	%	lateral	peak	7	14	10	10	7	8	7	8
	Rp	µm	amplitude	peak	2,19	0,56	1,38	0,63	1,80	1,22	0,94	0,76
	Rhsc(c=0.3um)	no.	lateral	peak	128,4	19,2	73,8	21,0	160,0	116,0	131,6	63,4
	Rk	µm	amplitude	core	1,47	0,33	0,90	0,32	1,30	0,66	0,51	0,41
	Rvk	µm	amplitude	valley	1,71	1,60	1,66	1,33	1,55	1,66	1,39	1,16
	Rmr2	%	lateral	valley	80	84	82	81	80	75	68	74
	Rv	µm	amplitude	valley	6,61	5,31	5,96	4,30	5,43	5,65	3,79	4,24
	Rvc(c=-1um)	no.	lateral	valley	35,8	16,0	25,9	18,0	44,0	32,4	37,6	30,4
AMPLITUDE	Rt	µm	amplitude	extreme	8,80	5,88	7,34	4,94	7,23	6,86	4,73	5,00
	Rz	µm	amplitude	extreme	7,05	4,82	5,93	4,45	6,28	5,58	4,03	4,03
	Ra	µm	amplitude	mean	0,64	0,28	0,46	0,27	0,57	0,47	0,45	0,33
OTHER	Rmr (5%, 1um)	%	lateral	valley	60	92	76	93	67	83	83	90
	a (width)	µm	lateral	valley	44,92	51,41	48,16	42,13	34,84	31,88	31,30	27,98
	d (distance)	µm	lateral	valley	167,18	283,10	225,14	271,29	136,35	171,50	147,41	173,67
	C (depth)	µm	amplitude	valley	2,36	2,15	2,25	2,14	2,11	2,28	1,83	1,70
	ng (no. of)	no.	lateral	valley	28,4	14,8	21,6	16,2	35,6	27,8	33,0	27,6
	Wt	µm	amplitude	extreme	0,04	0,03	0,04	0,03	0,03	0,03	0,02	0,02

Table 1 For 500X of magnification, blechmantel and irregularities have good accuracy with a reasonable dispersion

Parameter correlation

High regression coefficients, R, between parameters (R= 0.87, R^2=0.72 and higher) indicate that parameters either are measure of the same property or that they are changing in similar ways as in this study, roughness level, operating pressure and unworn- or worn status change. A linear correlation of the two image analysis parameters blechmantel ratio and irregularities reveal a relatively low correlation to the different roughness parameters (table. 1).

For the **image parameters** the maximum regression coefficient of 76% (R^2=0.58) indicate a strong separate description of features not measured by the other profile characterizing parameters. I.e. image parameter are essential to describe lateral features not possible to measure with the stylus technique.

Table 2

		IMAGE		PEAK				CORE	VALLEY				EXTREME-MEAN			GOETZE					
		blech ratio	**irregularities ratio**	**Rpk**	**Rmr1**	**Rp**	**Rhsc**	**Rk**	**Rvk**	**Rmr2**	**Rv**	**Rvc**	**Rt**	**Rz**	**Ra**	**Tpa**	**a**	**d**	**C**	**ng**	**Wt**
IMAGE	**blech ratio**	**100%**	76%	62%	-56%	68%	49%	60%	27%	-26%	49%	47%	60%	50%	69%	-64%	-16%	-55%	20%	43%	33%
	irregularities ratio	76%	**100%**	42%	-74%	66%	68%	60%	12%	-34%	38%	72%	51%	47%	68%	-58%	-55%	-78%	6%	70%	9%
PEAK	**Rpk**	62%	42%	**100%**	-37%	93%	67%	92%	77%	17%	77%	55%	89%	88%	92%	-95%	29%	-44%	60%	43%	68%
	Rmr1	-56%	-74%	-37%	**100%**	-57%	-85%	-52%	13%	67%	7%	-90%	-18%	-21%	-68%	56%	73%	93%	21%	-91%	22%
	Rp	68%	66%	93%	-57%	**100%**	76%	99%	61%	12%	74%	69%	89%	91%	97%	-99%	6%	-60%	53%	58%	61%
	Rhsc	49%	68%	67%	-85%	76%	**100%**	73%	31%	-46%	25%	97%	47%	50%	88%	-76%	-47%	-93%	7%	94%	3%
CORE	**Rk**	60%	60%	92%	-52%	99%	73%	**100%**	60%	19%	74%	67%	89%	91%	94%	-99%	11%	-55%	51%	55%	62%
VALLEY	**Rvk**	27%	12%	77%	13%	61%	31%	60%	**100%**	47%	87%	10%	83%	81%	58%	-59%	56%	1%	88%	-2%	80%
	Rmr2	-26%	-34%	17%	67%	12%	-46%	19%	47%	**100%**	59%	-53%	44%	47%	-10%	-11%	85%	67%	66%	-64%	73%
	Rv	49%	38%	77%	7%	74%	25%	74%	87%	59%	**100%**	12%	96%	93%	63%	-69%	53%	-3%	85%	-2%	89%
	Rvc	47%	72%	55%	-90%	69%	97%	67%	10%	-53%	12%	**100%**	35%	38%	81%	-70%	-60%	-97%	-13%	99%	-12%
EXTREME-MEAN	**Rt**	60%	51%	89%	-18%	89%	47%	89%	83%	44%	96%	35%	**100%**	99%	80%	-86%	38%	-26%	78%	22%	84%
	Rz	50%	47%	88%	-21%	91%	50%	91%	81%	47%	93%	38%	99%	**100%**	81%	-88%	37%	-26%	79%	24%	84%
	Ra	69%	68%	92%	-68%	97%	88%	94%	58%	-10%	63%	81%	80%	81%	**100%**	-96%	-9%	-73%	42%	72%	45%
GOETZE	**Tpa**	-64%	-58%	-95%	56%	-99%	-76%	-99%	-59%	-11%	-69%	-70%	-86%	-88%	-96%	**100%**	-10%	59%	-47%	-59%	-58%
	a	-16%	-55%	29%	73%	6%	-47%	11%	56%	85%	53%	-60%	38%	37%	-9%	-10%	**100%**	72%	64%	-70%	73%
	d	-55%	-78%	-44%	93%	-60%	-93%	-55%	1%	67%	-3%	-97%	-26%	-26%	-73%	59%	72%	**100%**	24%	-99%	24%
	C	20%	6%	60%	21%	53%	7%	51%	88%	66%	85%	-13%	78%	79%	42%	-47%	64%	24%	**100%**	-26%	90%
	ng	43%	70%	43%	-91%	58%	94%	55%	-2%	-64%	-2%	99%	22%	24%	72%	-59%	-70%	-99%	-26%	**100%**	-27%
	Wt	33%	9%	68%	22%	61%	3%	62%	80%	73%	89%	-12%	84%	84%	45%	-58%	73%	24%	90%	-27%	**100%**

Table 2. For 500X of magnification, blechmantel and irregularities have good accuracy with a reasonable dispersion

Within the **Peak parameter family** a relatively strong correlation between the Rpk- and the Rp-parameters can be seen (R=0.93). The parameters both express amplitude of the peak portion of the liner and can be mutually replaced.

Peak parameters Rp and Rpk are highly correlated to the core roughness Rk, (R=0.99 and R=0.93) while the relation to the valley parameters are weaker as exemplified with an average regression coefficient of R=0.50 for the eight peak and valley parameters.

The core parameter Rk have not only the strong relation to the peak parameters as mentioned above but also a non existent or weak relation to valley parameters. The stronger correlation to peak parts of the cylinder liner is complemented with an R=0.99 to the bearing parameter Rmr (1um, 5%) as well as the strong correlation to average amplitude parameter Ra (R=0.94) and the extreme amplitude parameters Rt and Rz (R=0.89 and R=0.91).

Valley parameters Rv and Rvk are very much stating the same fact about the surface profile and have an R of 0.87 and a high correlation to Rt and Rz (R=0.96, R=0.93) for the Rv parameter but a low correlation to the peak parameters, constituting a separation of the valley and peak performance under the conditions tested in this study.

The average- and extreme ISO amplitude parameters show a high correlation to parameters from all the peak-, core- and valley parameter groups. The broad correlation spectra between the average and extreme amplitude parameters indicate the use of more specialized peak-, core-, and valley descriptors like the parameters in this study to complete the picture of the cylinder liner surface before- and after usage.

The non-standardised valley- (a, d, C, and ng), as well as Rmr and Wt-parameters show a high coorelation (R=0.99) between the number of grooves, ng- and distance between grooves, d- and R=0.90 for the Waviness, Wt, to groove depth, C-parameters. Naturally the non-standardised valley parameters correlate best with the standard valley parameters.

The bearing parameter Rmr at 5% reference and at 1um depth show R=0.95 and R=0.99 for the peak amplitude parameters Rpk and Rp, indicating this parameters possibility to be an alternative to the two.

Topography transition from unworn to worn state

Peaks are the together with the core portion of the surface naturally the part of the cylinder liner who immediately will be “hit” by the piston-ring and oil dynamic effect and modified by tribochemical reactions.

The SEM-Image and stylus topography analysis verify the qualitative assumptions above but in addition a quantitative measure and segmentation of the wear state can be made with relation to the operating conditions like different combustion pressure (high pressure-diesel engine and lower pressure-petrol engine), and initial roughness levels (rough and smooth).

Peaks are defined by Rpk (reduced peak height) and Rhsc (high spot count). Rhsc is generally higher in this test for the petrol liners (132 and 63 for the rough- and smooth worn petrol engines) than for the high pressure diesel liners (19 and 21). In other words, an average of diesel liner decrease for rough and smooth liners' Rhsc with 410% compared with 73% for the petrol liner.

Core roughness, Rk, in average, decrease more for diesel liners than for petrol liners. In average (rough and smooth liners) the diesel core roughness decrease 265% while the petrol liners average on a 60% decrease. Notable is that, rougher surfaces decrease Rk more than smoother surfaces but the low pressure petrol liner stay at Rk=0.66um and Rk=0.41um for the rough- and smooth textures while high pressure rough and smooth diesel liners smoothens down to a similar level of Rk=0.33um and 0.31um. The higher petrol liner Rk in the end of the test either indicate a non-finished run-in state or a combustion pressure and piston-ring material unable to decrease the plateau roughness values at the diesel liner finishing Rk-levels.

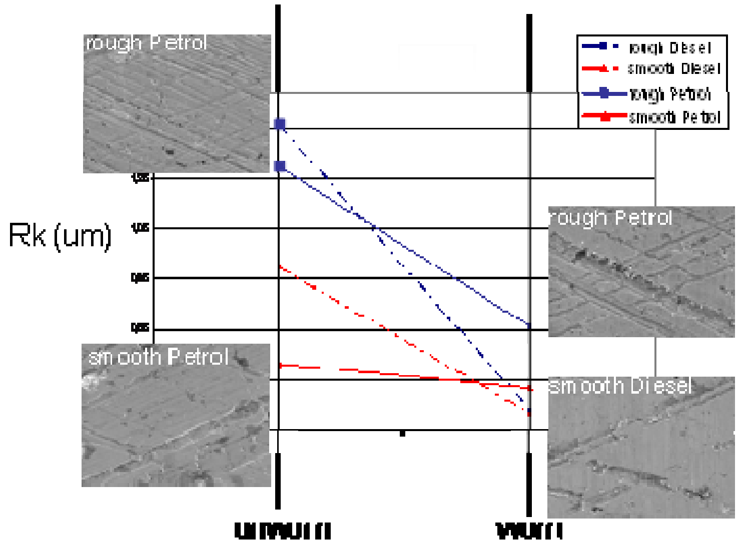


Fig. 11 Rk values before and after testing.

The valley roughness characterized by the C-parameter (valley depth) and Rvk, remain approximately on the same level for all liners (10% and lower increase of the C-parameter and a 7% to 25% decrease for the Rvk parameter. The most significant change is the number of grooves –ng and corresponding valley count parameter –Rvc who both decrease significant (-92% and -124% respectively).

For valley characterization, the **non-standardised valley parameters** follow the standardized ones but in return deliver more detailed data about mean valley width (a), distance (d), number (ng) and depth (C).

The Ra-parameter is sensitive only to the big changes of peak- and valley amplitudes for the high pressure diesel liners (129% for the rough liner and 71% for the smooth liner). Decrease of Ra values are much smaller for the petrol liners (21% for the rough liner and 36% for the smooth liner) and further more, no distinction between core, valley and peak changes can be determined using the Ra-parameter.

The extreme amplitude parameters Rt and Rz show the same behavior as the Ra-parameter and again the parameters average out peak-, core- and valley amplitude changes and correlate highly (table 444) to peak-(Rpk), core-(Rk) and valley-(Rvk) parameters.

Image parameters Blechmantel- and Irregularities ratio show a high sensitivity to varying conditions and decrease 1180% to 100% for the diesel liners while the parameters increase between 106% to 18% for all the petrol liners. A probable cause is the more severe diesel high pressure run-in conditions able to effectively "truncate" the plateaux and remove residing plastically deformed un-cut honing residues while the less severe petrol liner conditions not manage to remove the blechmantel and irregularities in an important extent.

Conclusions

SEM quantitative image analysis can be used for groove and background separation of honed structures.

The Hough transform is useful for groove analysis (orientation, balance, interrupts)

Two-dimensional profilometry give additional information of grove vertical- and horizontal measures.

The profilometrical parameters give detailed information of the vertical peak-, core- and valley regions, separately or as average.

Individual groove information regarding width, distance, number and depth are special groove features possible to measure.

The parameters used, monitor the wear as a peak and core profile phenomena and valley regions are left relatively intact.

Profiling Rpk,Rk, Rvk, and C parameters together with SEM image analysis parameters (blechmantel) give information of the development of the vertical peak, core, valley and lateral properties of a liner surface.

Traditional roughness parameters like Ra, Rt, and Rz indicate change of the liner surface due to wear but are to related to each other and other parameters to distinguish wear regions and further, the wear of the low pressure petrol liners

Low pressure petrol liners in this test either still are undergoing run-in wear or the final roughness will be rougher than the high pressure diesel liners.

Future

The usage of the latest 3D topography parameters as suggested by Blunt et. al. is currently being implemented and should be tested as a compliment to the combined SEM- and stylus techniques suggested in this study.

The number of measurements to achieve significant measuring values need to be improved to ensure the general application of liner characterisation.
Further test need to be carried out to clear out the last conclusion above, wether the low pressure liners will stabilise on higher core roughness values (Rk) or not. The Rk believed to control both friction and oil consumption, hence a parameter important to clearify in this case.

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