Height-Independent Topographic Parameters of Worn Surfaces

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Abstract: *Surface microtopography plays a dual role in the course of friction and wear processes. It affects the contact and temperature conditions, and it undergoes significant changes in accordance with the wear mechanism. Fractal dimension (Df), root mean square gradient (Sdq), surface area ratio (Sdr) and surface kurtosis (Sku) parameters of microtopographies provides opportunities for understanding more deeply the wear processes independently from the amplitude of the roughness. Wear experiments and surface roughness measurements before and after wear were performed. Investigations extended to wear in the course of the non-lubricated ferrodo-steel material pairs, and lubricated camshaft-bushing pairs.*

Keywords: *wear; microtopography; power spectral density; fractal dimension; 3D parameters*

1 Introduction

Efficient research in the course of the past decades has provided experts involved in surface microtopography research with a number of tools and methods to design an operationally optimized surface. At the same time, this knowledge is utilized only to a small degree in the analysis and control of tribological processes. Characteristically, designers continue to content themselves by requiring few – first of all height-dependent – roughness parameters [1].

In the first half of the 90s, computers of adequate speed of operation and processing softwares became increasingly available, make it possible to realize 3D surface characterisation. In the literature different directives can be found none of them has become widely used. Beside the extension of 2D parameter based technique to 3D many other new parameters and methods have been developed. One is the power spectral density (PSD) technique when “global” surface characterisation is carried out using complex mathematical tools. PSD provides full length scale analysis which takes into consideration not only the dominant topographic elements but also the submicro features, in contrast with traditionally surface characterisation methods. The fractal dimension derived from PSD topography seems to be an efficient tool for characterization. Some topographic parameters such as *Sdr* connected exclusively to 3D topographic analysis, but some others have 2D pairs (for instance *Sdq* or *Sku*).

In the course of friction and wear processes, surface topography plays a dual role. On the one hand, it affects the contact and temperature conditions occurring between the contacting surfaces which determine the tribological process together with a third body; on the other hand, it undergoes significant changes in accordance with the wear mechanism operating between the surfaces.

In the present study topographical measurements and special 3D parameter-based characterizations were performed to study the changes of microtopographies in wear. Laboratory wear tests of ferrodo-steel sliding pair were carried out and also industrial worn machine elements were investigated. Fractal dimension (*Df*), root mean square (RMS) gradient (*Sdq*), surface area ratio (*Sdr*) and surface kurtosis (*Sku*) of topographies before and after wear were analysed and compared.

2 Investigated Topographies

The first part of investigation was the wear test of ferrodo-steel sliding pair. Steel (55Si7) sliding tracks were used for the tests, on which 18 mm ferodo specimens were slid. The steel had ground surfaces. Two different grinding wheels were used for producing ‘fine’ (sign: F) and ‘rough’ (sign: R) surfaces. Two machining directions were used: one of them was perpendicular to (sign: N) while the other was parallel (sign: P) with the sliding direction. The stroke of the sliding was 180 mm and the load was 1000 N. The sliding speed was 50 mm/s. No lubrication was applied. First test series were slide for 2 hours while the second test series were slide for 6 hours. Steel track microtopography was recorded at two different places using a Mahr Perthen Concept 3D type stylus instrument. The size of the surface measured was 1x1 mm and the sampling distance was 2 μm in both directions. Measurements were performed on identical surface sections before and after the wear process, therefore the changes of a given surface section can be traced accurately, not only statistically, in the course of the wear process.

The second part of investigations was the topographic measurements of camshaft-bushing pair. Original and worn one was measured from both of them. The worn camshaft and thrust bushing was operated 115000 km in a car. Measurement topography size and also the sampling distance were similar than in case of steel sliding track. Table 1 summarise the wear tests parameters and set-up of topographic measurements.

Table 1

Wear test and measuring conditions

Sliding pair	Speci-men	Wear time	Machining vs. Sliding direction	Average roughness of original topography	Repetitions of topography measurements	Sign
Ferrodo-steel	Steel	2 h	Paralell (P)	Fine (F) Sa≅0.2 µm	2	2hPF_A
						2hPF_B
				Rough (R) Sa≅1.6 µm	2	2hPR_C
						2hPR_D
			Perpendicular (N)	(F) Sa≅0.2 µm	2	2hNF_E..F
				(R) Sa≅1.6 µm	2	2hNR_G..H
		6h	Perpendicular (N)	(F) Sa≅0.1 µm	6	6hNF_I..N
Cam-shaft - Bushing	Cam	115000 km	Paralell (P)	(F) Sa≅0.3 µm	1	Ch115PF_O
	Bush-ing		Paralell (P)	Very fine (VF) Sa≅0.04 µm	1	Bu115PWF_P

Figures 1-3 show some topographies. The original microtopography of 2hNF_E surface disappeared and new surface texture was formed in accordance with the direction of relative movement. The scratches formed seem “fine” and uniform. In case of Figure 2. the original surface texture has not disappeared, but the peak zone of microtopography changed: scratches were formed in the sliding direction. Figure 3 show chamshaft and bushing surfaces formed by abrasive wear similar than steel surface in Figures 1 and 2. Scratches are laying long on the surfaces, and they are not too deep, so abrasive mild wear can be supposed in all cases.

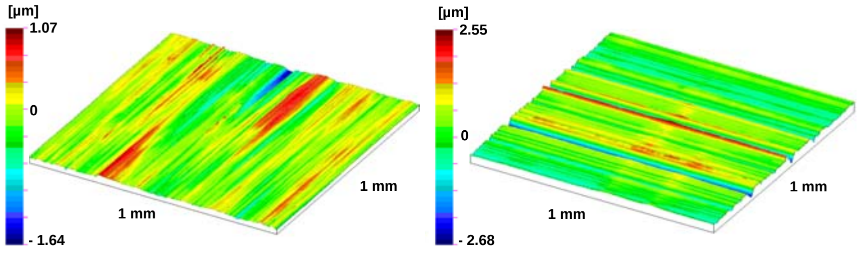

Figure 1

2hNF_E surface before wear and after 2 hour sliding

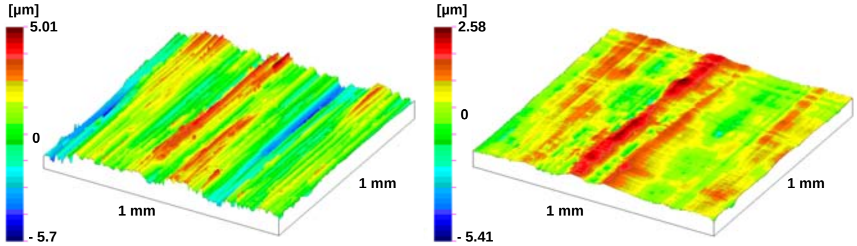

Figure 2
2hNR_H surface before wear and after 2 hour sliding

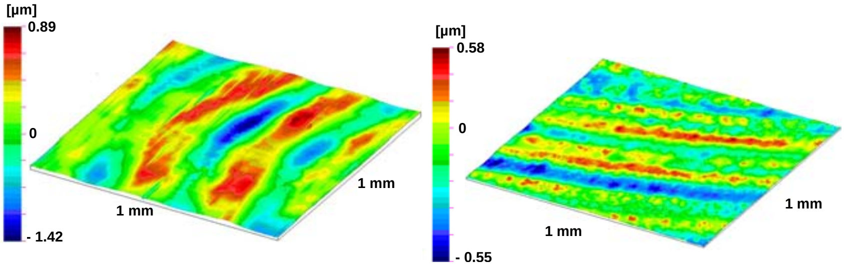

Figure 3
Worn surface of chamshaft (Ch115PF_O) and thrust bushing (Bu115PWF_P)

3 Characterisation Technique

To characterize the measured topographies an algorithm was developed in cooperation with Department of Machine and Industrial Product Design, Budapest University of Technology and Economics and interpreted as a parametric-based 3D surface and PSD analysis software. Theoretical base of 3D parameters and PSD analysis are summarised as follows. Details can be found in [2, 3 and 4].

The root mean square gradient, *Sdq*, is the RMS-value of the surface slope within the sampling area, and is defined as (1).

$$Sdq=\sqrt{\frac{1}{(M-1)(N-1)}\sum_{j=2}^{N}\sum_{i=2}^{M}\left(\frac{z(x_i,y_j)-z(x_{i-1},y_{j-1})}{\Delta x}\right)^2+\left(\frac{z(x_i,y_j)-z(x_{i-1},y_{j-1})}{\Delta y}\right)^2} \quad (1)$$

where $z(x_i, y_j)$ is the height coordinate located in x_i, y_j, M is the number of points in profile, N is number of profiles, Δx, Δy sampling distances.

The surfaces area ratio, *Sdr*, expresses the increment of the interfacial surface area relative to the area of the projected plane (2).

$$Sdr = \frac{\sum_{j=1}^{N-1}\sum_{i=1}^{M-1} A_{i,j} - (M-1)(N-1)\Delta x \Delta y}{(M-1)(N-1)\Delta x \Delta y} \qquad (2)$$

The surface kurtosis, *Sku*, describes the "peakedness" of the surface topography, and is defined as (3), where Sq is the RMS value of topography. For Gaussian height distributions *Sku* approaches 3.0 when increasing the number of pixels. Smaller values indicate broader height distributions.

$$Sku = \frac{1}{MNSq^4}\sum_{j=1}^{N}\sum_{i=1}^{M} z^4(x_i, y_j) \qquad (3)$$

PSD analysis transforms the profile from the spatial domain to frequency one using Fourier transformation. Transformation gives complex result The power spectral density assigns an “amplitude” – magnitude of the complex number – to the frequency pair p_k, q_l. There are two possibilities of showing results. One is to represent the amplitude of PSD in the function of wavelength. The other prevalent method is logarithmic scale frequency-PSD amplitude visualization. In the second method the height frequency range of the curve can be approximated by a line. The slope of the line is in correlation with the fractal dimension of surface. Wavelengths smaller than the highest dominant wavelength plays a considerable role. PSD amplitude becomes constant – the self-affinity character of the surface disappears – in a lower wavelength range. The slope of fitted line (*s*) to PSD curve has correlation with fractal dimension of surface according to (4).

$$Df = 4 + \frac{s}{2} \qquad (4)$$

4 Results

Changes of *Sdq* and *Sdr* parameter in wear are summarised in Table 2 and Figures 4 and 5. Both parameters change dramatically. Some cases the change is higher than 100%. Sdr parameter is very sensitive for wear: its change is higher than 50% in all cases. In cases of A, B, G, H both parameters increases, although the wear process of A-H specimens are the same. The *Sdq* value after wear – using similar test set up – becomes similar. In case of A-H this value is in range 3.62-7.08°, although the original topographies have wide range (2.73-12.76°) of this parameter. Analysing the results of six-hour wear process the conclusion is the same.

It is also interesting that behaviour of *Sdq* and *Sdr* parameters is uniform. Examining the definitions of these parameters the experinece is understadable. If the topogrpahy has higher RMS gradient it means, that enveloping surface is higher so *Sdr* parameter also has higher value. Because of the very sensitive character of *Sdr* in general case *Sdq* seems more effective.

Table 2
RMS slope and surface area ratio before and after wear

Sign	*Sdq* [°]		Change in %	*Sdr* [-]		Change in %
	before wear	after wear		before wear	after wear	
2hPF_A	2.79	5.37	-92.47	0.06	0.36	-500.0
2hPF_B	3.12	3.62	-16.03	0.09	0.14	-55.6
2hPR_C	11.07	6.31	43.00	1.82	0.54	70.3
2hPR_D	13.35	7.08	46.97	2.69	0.69	74.3
2hNF_E	11.85	5.02	57.64	2.05	0.32	84.4
2hNF_F	12.56	5.20	58.60	2.33	0.35	85.0
2hNR_G	2.73	6.77	-147.99	0.06	0.62	-933.3
2hNR_H	2.90	5.41	-86.55	0.08	0.38	-375.0
6hNF_I	8.55	1.26	85.26	1.05	0.003	99.7
6hNF_J	9.23	1.30	85.92	1.24	0.004	99.7
6hNF_K	8.49	1.63	80.80	1.04	0.011	98.9
6hNF_L	8.55	1.14	86.67	1.05	0.002	99.8
6hNF_M	8.52	1.54	81.92	1.04	0.016	98.5
6hNF_N	8.24	1.47	82.16	0.97	0.011	98.9
Ch115PF_O	5.25	1.30	75.24	0.35	0.012	96.57
Bu115PWF_P	0.33	0.70	-112.12	0.0001	0.0002	-100.00

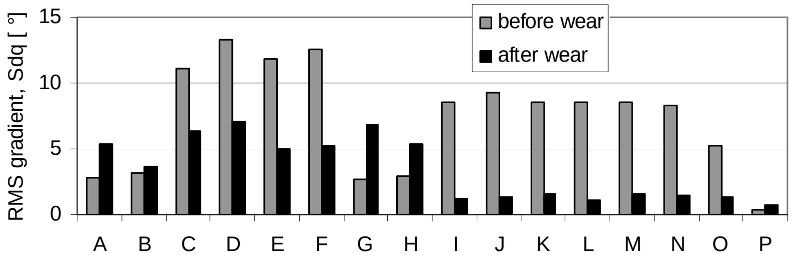

Figure 4
RMS slope before and after wear

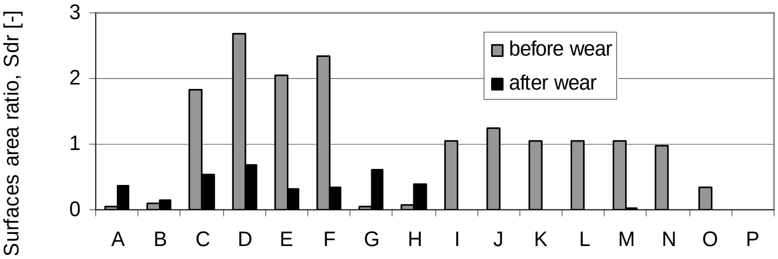

Figure 5
Surface area ratio before and after wear

Fractal dimensions of topographies before and after wear, as the results of analysis were presented in [5]. Now its correlation with other parameters is analysed. Table 3 summarises the results and Figure 6 shows the fractal dimension before and after wear, while Figure 7 shows the surface kurtosis.

Table 3
Fractaldimension and surface kurtosis before and after wear

Sign	*Df* [-]		Change in %	*Sku* [-]		Change in %
	before wear	after wear		before wear	after wear	
2hPF_A	2.78	2.80	0.72	3.14	12.00	-282.17
2hPF_B	2.88	2.76	-4.13	3.57	3.94	-10.36
2hPR_C	2.89	2.71	-6.17	2.00	2.26	-13.00
2hPR_D	2.80	2.67	-4.49	2.42	3.18	-31.40
2hNF_E	2.77	2.80	0.89	3.40	8.74	-157.06
2hNF_F	2.73	2.68	-1.60	5.02	4.54	9.56
2hNR_G	2.72	2.57	-5.58	2.18	2.88	-32.11
2hNR_H	2.84	2.65	-6.67	3.07	4.25	-38.44
6hNF_I	2.84	2.65	-6.82	3.20	3.05	4.69
6hNF_J	2.92	2.58	-11.65	3.08	3.77	-22.40
6hNF_K	2.87	2.52	-12.22	3.54	2.48	29.94
6hNF_L	2.92	2.79	-4.40	3.38	2.86	15.38
6hNF_M	2.79	2.99	7.19	3.80	5.83	-53.42
6hNF_N	2.80	2.76	-1.37	4.94	4.70	4.86
Ch115PF_O	2.78	2.43	-12.72	3.62	2.91	19.61
Bu115PWF_P	2.92	2.31	-20.88	3.94	2.51	36.29

As was concluded in [5] fractal dimension – in contrast with other parameters – have correlation with wear: *Df* decreased in examined wear processes. Only three case were where *Df* increased, but topographies in these cases have deep groves formed by wear particles.

Increase of *Sku* paramer was supposed before the tests, because of platou-like character of mild wear surfaces. The results do not confirm this statement. The change of kurtosis was minimal, and in some cases the parameter decreased. Topographies of six-hour wear process (sign I-N) have kurtosis between 3.08–4.94 before wear. However the same process was carried out *Sku* chenged between -53.42 and 29.94 %. No correlation with wear process was found. Only one interesting thing must be mentioned: chanege of kurtosis was significant (more than 50%) in three cases. In these cases fractal dimension was increased. It means that not only the fractal analysis, but parameter surface kurtosis is sensitive for deep grooves of topographies. The fourth power in definiton of *Sku* explain this phenomenon.

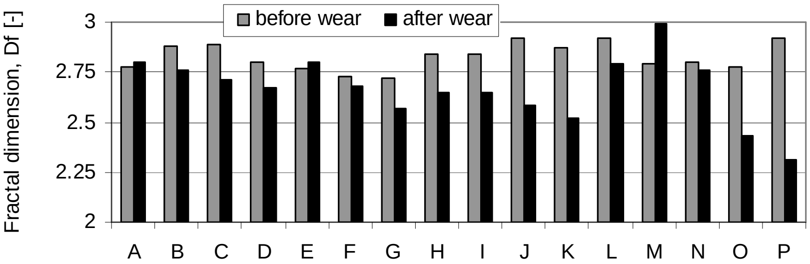

Figure 6
Fractal dimension before and after wear

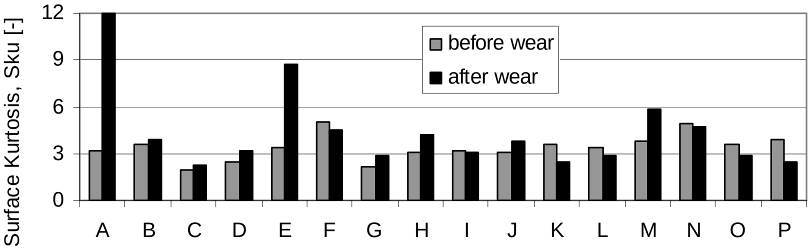

Figure 7
Surface curtosis before and after wear

Conclusions

Results can be summarised as follows:

Root mean squere slope (*Sdq*) and areal ratio (*Sdr*) parameters characterise similar features of topogrpahies, but *Sdr* parameter is more sensitive for changes.

Fractal dimension (*Df*) of surfaces was decreased in case of mild wear, but special surface features – such as deep groves – increased its values.

Surface kurtosis (*Sku*) has no correlation with wear process, but it is sensitive for appearance of deep groves: *Sku* value draatrically increased.

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