Fractal Characterisation of Worn Surfaces

Árpád Czifra, István Barányi

Donát Bánki Faculty of Mechanical and Safety Engineering, Óbuda University, Népszínház u. 8, H-1081 Budapest, Hungary
czifra.arpad@bgk.uni-obuda.hu

***Abstract**: Tribological behaviour – friction, wear and lubrication – of machine elements highly depend on the operating state and also the original topography of working pair. In our study wear experiments and surface roughness measurements before and after wear were performed. Investigations extended to wear in the course of the non-lubricated ceramic-steel, ferrodo-steel and bronze-steel material pairs. Fractal dimension of topographies before and after wear were calculated using power spectral density, height-difference correlation and scale-analysis methods. The aim of this study was to compare the capability of three different surface characterisation techniques through the analysis of worn surfaces and also to examine the changes of fractal character of topographies in wear.*

***Keywords**: microtopography, power spectrum, height-difference correlation, wear*

1 Introduction

Traditionally and in accordance with international standards, the micro-geometry of operating surfaces, in the most cases, is characterized in two dimensions; however its information content is limited. In the first half of the 90s, computers of adequate speed of operation and processing softwares became increasingly available; making it possible to realize 3D surface characterisation. Beside the extension of 2D parameter based technique to 3D [1] many other methods have been developed. Nowadays – beyond the parameter based technique – two dominant research trends can be observed. One is the technique when the local features of topographies are characterized based on the identification of asperities and scratches, while the other is the “global” surface characterisation method using complex mathematical tools.

Information obtained from the micro and nano-topographies of operating surfaces appears as input in today’s friction and wear models. In [2], authors take surface topography into account through the power spectrum of the real surface when calculating the hysteretic coefficient of friction. These models are based on fractal theory supposing that fractal can characterise the topography in full length scale.

At this point, it must be mentioned that there are cases when fractal analysis of engeenering surfaces shows constant fractal dimension in the whole length-scale while, in other cases, the it has bilinear form i.e. the fractal dimension is different within the two scaling regimes [3]. It can be concluded that output of the friction models depends strongly on the reliability of the surface roughness model applied as input data.

The aim of this study is to compare the capability and results of three different surface characterisation techniques (parameter based technique, slicing method and PSD analysis) through the analysis of brake plungers manufactured by three different surface finishing techniques (cork-wheel, sand paper, rolling). Although these techniques are known such a comparison has not been made yet. Micro- and nano-scale surface topographies were measured by stylus instrument and atomic force microscope (AFM).

The aim of this study was to compare the capability of three different surface characterisation techniques through the analysis of worn surfaces and also to examine the changes of fractal character of topographies in wear, continueing started preject presented in [4].

2 Wear Tests and Surface Measurements

Investigations extended to wear in the course of the non-lubricated ceramic-steel, ferrodo-steel and bronze-steel material pairs. Table 1 summarizes the material pairs and wear test conditions and also the surface measurements.

Table 1

Wear and measurement conditions

Material pair	Specimen	Repeti-tions	Operating conditions	Topography measurements
Steel-ferrodo	Steel (55Si7) Sign: FK	3	pin-on-plate alternating friction and wear machine; no lubrication p≈4 MPa; v=50 mm/s 6 hour (180 mm stroke)	before wear: 6 after wear: 6 Same part of surface before and after wear.
Steel-bronze	Steel (K1) Sign: K1	2	specimens on slope no lubrication p≈0.0125 MPa; 3500 m sliding	before: 2; after: 1
	Bronze Sign: BR			before: 2; after: 2 Same part.
Steel-ceramic	Steel (100Cr6) Sign: CR	1	clutch modelling system no lubrication 300 cycle 0-1500 1/min F=150 N	before: 4; after: 4
	Ceramic (Al_2O_3) Sign: AL			before: 4; after: 4
Number of topographies measured:				before: 18; after: 17

In all cases 1 by 1 mm surface topography was measured with 2 µm sampling in both direction. Measurements were performed in Mahr Perthometer Concept stylus instrument. Details of wear tests can be found in [5, 6, 7].

3 Surface Characterisation Techniques

Three different technique were used to calculate fractal dimension of topographies.

Power spectral density analysis of topographies is based on 2D discrete Fourier transformation (DFT) can be written as follows:

$$F(q_x, q_y) = \Delta y \cdot \Delta x \sum_{d=1}^{N} \sum_{c=1}^{M} z(x_c, y_d) e^{-i2\pi(x_c q_x + y_d q_y)} \qquad (1)$$

DFT gives complex results, so PSD 'amplitude' is calculated. Showing the PSD results logarithmic scale is used. If (2) the PSD topography can be reduced to PSD curve (see Fig.1).

$$q = \sqrt{q_x^2 + q_y^2} \qquad (2)$$

The slope (s_P) of the straight line fitted to PSD curve has correlation with fractal dimension of surface topography according to eq. (3):

$$Df_P = 4 + \frac{s_P}{2} \qquad (3)$$

Topographic PSD represents the whole topography in frequency scale not only the average of frequency analysis of profiles. It means that there is not any dominant direction in analysis. PSD curve contains all points of PSD surface.

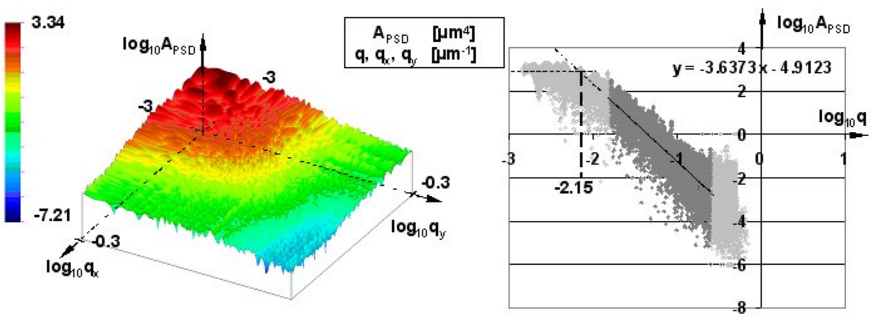

Figure 1

Interpretation of PSD results

HDCF can be calculated as (4), where λ is the wavelength, $z(x)$ is the height value of profile in x, $z(x+\lambda)$ is the height value of profile in $(x+\lambda)$.

$$C_z(\lambda) = \left\langle \left(\left(z(x+\lambda) - z(x) \right)^2 \right\rangle \qquad (4)$$

The slope (s_H) of fitted line to HDCF curve has correlation with fractal dimension:

$$Df_H = 3 - \frac{s_H}{2} \qquad (5)$$

Figure 2. shows a representation of HDCF derived from a single profile rather than the whole topography. The average of single profile HDCF curves characterise the topography. Practical tribological gain of this aspect is to emphasize the direction that is of importance from point of view of operation.

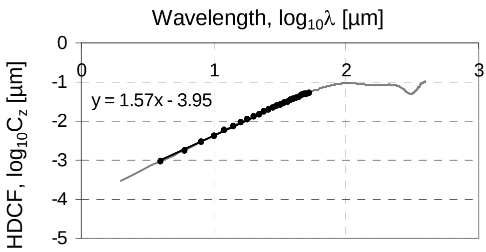

Figure 2
Height difference correlation function

Third method of fractal dimension calculation was the scale analysis [8]. Scale analysis is based on original fractal theory of Mandelbrot. The ratio of the surface of the topography and the measuring area is changes if the sampling distance vary. Area ratio as a function of sampling area gives similar results than PSD curve. Fractal dimension can be calculated according to eq. (6):

$$Df_S = 2 + 2s_S \qquad (6)$$

where ss is the slope of fitted line.

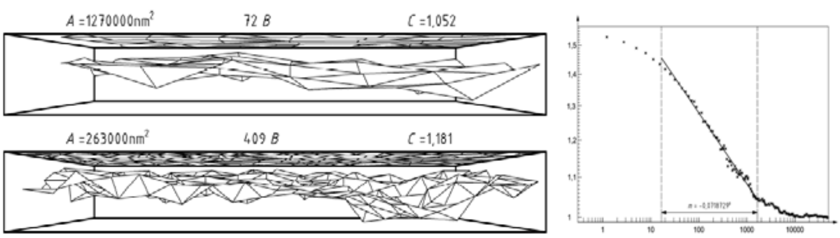

Figure 3
Scaly analysis of topogepahies [8]

In theoretical point of view this method is absolutely independent of measuring coordinate system or orientation of topography. In our case measured topography was mathematically modified using higher and higher sampling to get the scale – area ratio curve.

4 Results

4.1 Analysis of Worn Topographies

Figure 4. shows the one of the grinded steel surfaces (a part of steel-ferrodo pair) before and after wear. The original microtopogrphy disappeared and new surface texture was formed in accordance with the direction of relative movement. In this case abrasive scratches appeared on the surface in wear.

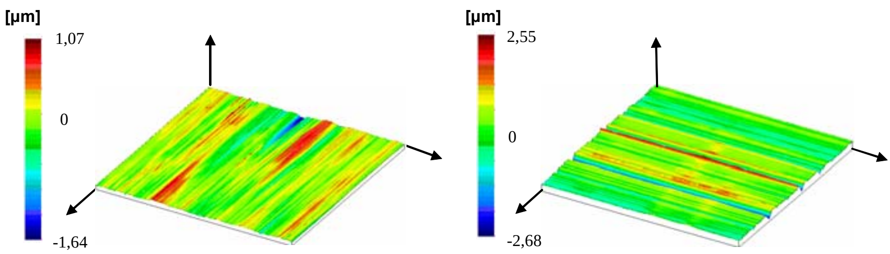

Figure 4

Grinded steel surface before the wear and after 120 min sliding under 1000 N loads (counterpart is ferrodo)

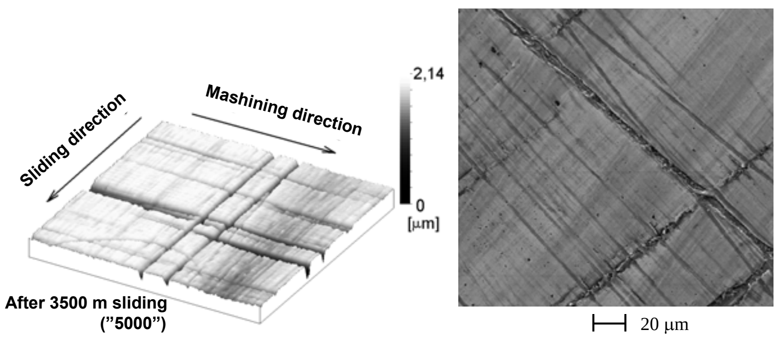

Figure 5

Bronze surface after wear; microtopogrpahy measured with stylus (left), measured with scanning electron microscope - SEM (right)

Figure 5. illustrates the bronze sliding after wear process. Only some very deep grooves remained from the original grinding: an almost completely new pattern was formed on the surface. A rough scratch along the middle of the SEM image, probably formed by a hard particle. Based on the topogrpahic examinations mild abrasive wear was occurred on grinded bronze part, but some bronze wear debris adhered to steel surface.

In clutch system no lubrication and height heat load caused drastically changes: thin transfer layer formed on surface on which tears and cracks can be found.. Figure 6. and 7. show one parts of a steel and also a ceramic surface.

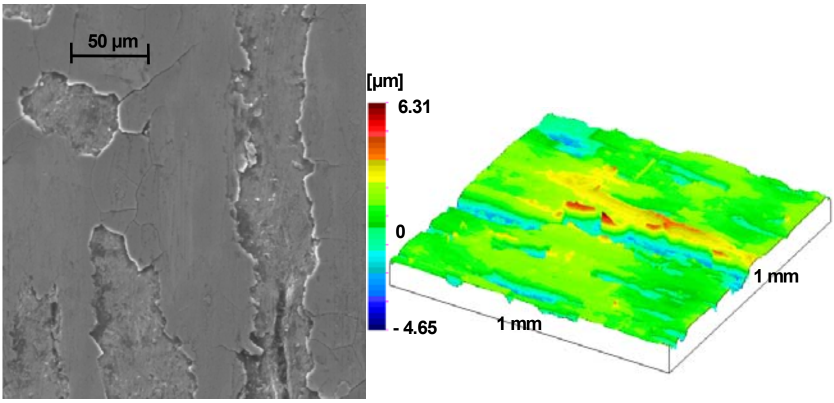

Figure 6
100Cr6 steel surface after wear with transfer film adhered on it; SEM image (left), stylus image (right)

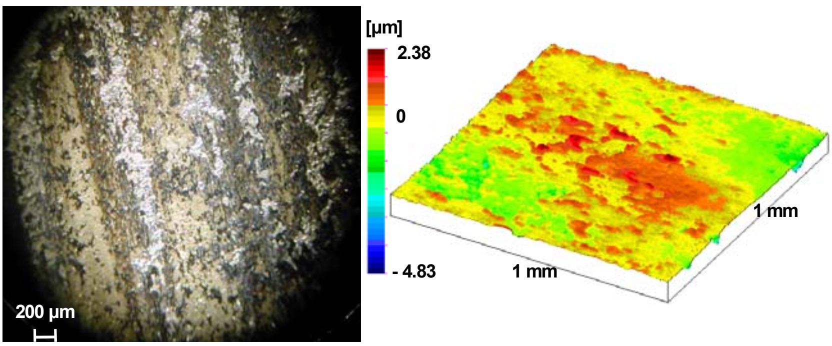

Figure 7
Cearamic surface after wear with transfer film adhered on it; optical microscope image (left), stylus image (right)

4.2 Fractal Dimension Results

Fractal dimension results and two well known topographic parameters are summarised in Table 2.

Table 2
Topographic parameters (Sa – average roughness, Sdq – average slope) and fractal dimensions of topographies

Sign	*Sa* [µm		*Sdq* [-]		Df_P [-]		Df_H [-]		Df_S [-]	
	before	after	before	after	before	after	before	after	before	after
FK_01A	0.61	0.24	8.56	1.26	2.79	2.69	2.28	2.42	2.28	-
FK_01B	0.63	0.26	9.23	1.30	2.82	2.70	2.29	2.29	2.37	-
FK_02A	0.59	0.33	8.49	1.63	2.84	2.66	2.28	2.39	2.28	-
FK_02B	0.63	0.14	8.55	1.14	2.85	2.89	2.35	2.56	2.28	-
FK_03A	0.76	0.12	8.52	1.54	2.82	2.98	2.36	2.49	2.29	-
FK_03B	0.65	0.14	8.24	1.47	2.78	2.78	2.33	2.6	2.28	-
K1_A	0.25	0.21	5.00	4.93	2.98	2.97	2.47	2.43	2.12	2.12
K1_B	0.24	-	5.69	-	2.91	-	2.40	-	2.16	-
BR_C	0.74	0.25	9.22	4.70	2.80	2.90	2.26	2.27	2.32	2.1
BR_D	0.53	0.18	7.43	3.93	2.73	2.90	2.26	2.28	2.21	2.06
CR_A	0.57	1.04	5.70	8.49	2.63	2.44	2.38	2.21	-	2.18
CR_B	0.60	1.24	5.98	7.47	2.67	2.30	2.48	2.22	-	2.16
CR_C	0.40	0.82	5.67	7.06	2.87	2.43	2.40	2.29	-	2.1
CR_D	0.38	1.32	5.40	6.41	2.88	2.48	2.41	2.30	2.07	2.13
AL_A	1.85	0.30	20.43	4.13	2.45	2.57	2.35	2.52	2.58	2.07
AL_B	1.70	0.28	19.02	1.89	2.45	2.24	2.38	2.53	2.58	-
AL_C	1.74	1.43	19.22	13.95	2.41	2.24	2.43	2.22	2.59	2.37
AL_D	1.88	0.45	18.92	6.61	2.47	2.56	2.42	2.31	2.55	2.13

Investigated topographies highly differ from each other. Average roughness (*Sa*) vary in range 0.12-1.88 µm, while average slope of surfaces (*Sdq*) is in range 1.14-20.43°. Unfortunately, fractal dimension relevant same topography may absolutely different. So, first of all, different methods and their adaptability must be examined. Based on results fractal dimension calculated with scale analysis

(Df_S) is in close connection with average slope of surface (*Sdq*).Correlation coefficient is: R^2=0.92. In my opinion, sampling distance should be lower to get more realistic Df_S values. Other considerable observation is the difference between Df_P and Df_H. There is only one case where good agreement can be found: surfaces of ceramic specimen before wear has Df_P in range 2.41-2.47 and Df_H in range 2.35-2.43. These topographies are isotropic, while other ones have orientation. In their original work [2] authors apply PSD analysis to calculate fractal dimension of isotropic surfaces. Based on results seems that Df_P has correct values only in surfaces that have no orientation. About HDCF one more thing must be mentioned: profiles are processed and it can be problematic in case of worn surfaces. Original topographies in most cases are oriented (for instance grinded surface, sign FK), which can be represented with one profile, or they are isotropic (e.g. Al2O3 ceramic) which also can be represented one profile, but worn topographies has different topographic features: adhered parts, deep grove across the fine texture, pitting, galling, spalling, denting type of wear. In this point of view the applicability of Df_H is limited. This may be the reason that no exact correlation has been found in fractal dimension and wear.

Figure 8. shows *Df* values in case of HDCF and PSD analysis. Only some results are in correlation (near the 45° line): these topographies are connected to isotropic surfaces.

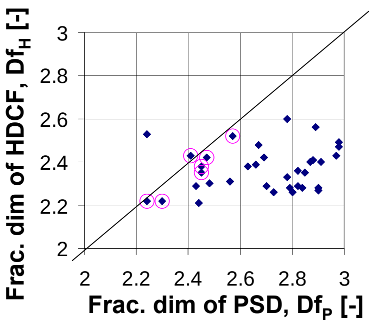

Figure 8
Fractal dimension results of PSD and HDCF analysis

Conclusions and furthers

Based on the test performed, the followings can be drawn:

- using fractal characterisation methods detailed above no correlation between fractal dimension and wear process can be observed;
- fractal dimension calculated with PSD can be used only in case of isotropic surfaces;
- fractal dimensions calculated with scale analysis have correlation with average slope of surface.

To use fractal analysis in characterisation of worn surfaces more developemet of methods is needed: topographic analysis of HDCF and correction of PSD in case of oriented surfaces.

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