ON THE DETERMINATION OF THE FRACTAL DIMENSION OF ROUGH SURFACES OF TITANIUM IMPLANTS

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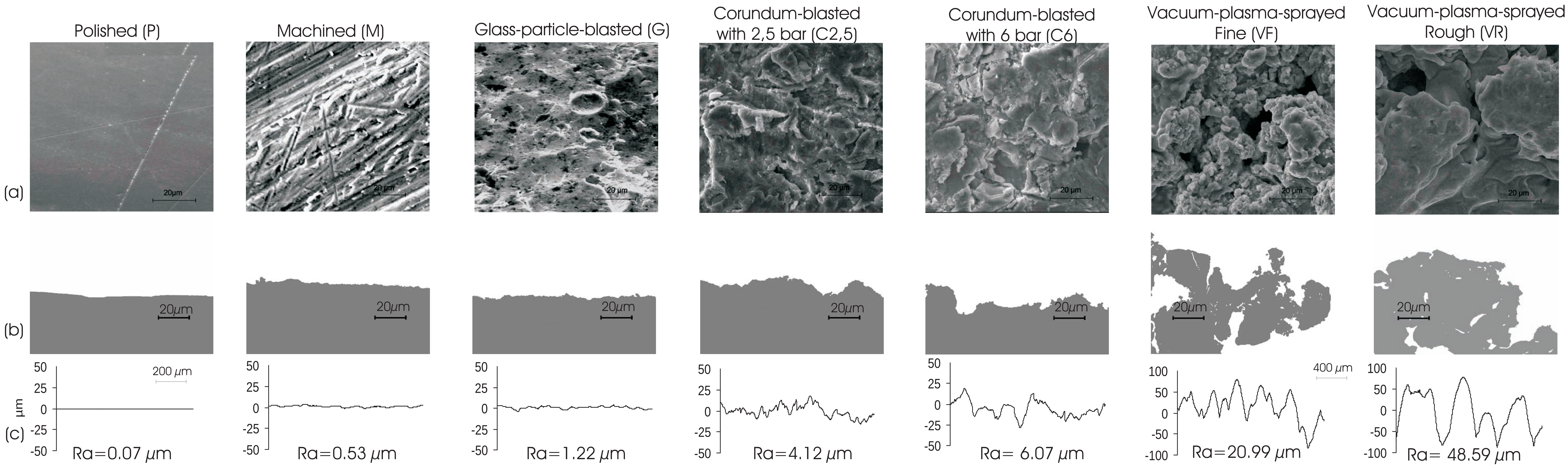
SEM-pictures (a) , cross sections (b) and surface profiles (c) of the analysed surface modifications



Surface profiling: HOMMEL-TESTER; sample length l_m=15 mm; scan rate 0.5 mm/s; calculation of average roughness Ra from the profile (ISO 4287/1)

Abstract

The determination of the fractal dimension D_F is an interesting way for the characterisation of rough surfaces.
Different structured titanium surfaces produced by smoothing (polishing), abrasive (blasting with glass and corundum particles under different pressures) and coating technologies (vacuum plasma spraying) were investigated.
Electrochemical impedance spectroscopy and linear sweep voltammetry were used to determine the fractal dimension of the titanium surfaces. Scanning electron microscopy pictures of cross sections were analysed by Digital Image Processing to verify the results of the electrochemical measurements.
Accompanying cell biological examinations were used to test whether the fractal dimension can be a relevant parameter for the description of the biocompatibility.
We demonstrate that differences in the fibronectin expression depending on surface roughness visualized in a Western Blot could be explained with the additional parameter fractal dimension.
This demonstrative example shows the possibility to predict the later cell behaviour and therefore the biocompatibility of material surfaces by an electrochemical experiment.

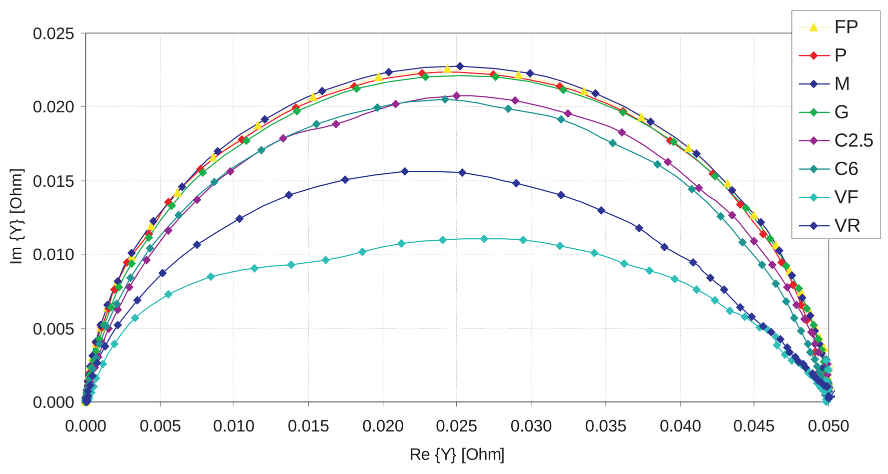
Electrochemical Impedance Spectroscopy (EIS)

electrolyte: phospate buffered saline PBS pH 7.2 not deaerated at 22 °C
working electrode geometrical area: 2.27 cm^2
reference system: SCE
frequency range: 1mHz to 10 kHz
single sine mode: ac amplitude 10 mV with respect to open-circuit-potential (OCP)
measuring system: ZAHNER IM6e + THALES software
equivalent circuits:
FP, P, M, G, C2.5, C6 => RE(Q1R1)
VF,VR => RE(Q1R1)(Q2R2)
relation between the exponent n of the Constant phase element (Q) and D_F for a blocking electrode :

$$n \quad \frac{1}{D_F \quad 1} \qquad [1]$$

[1] T. PAJKOSSY, L. NYIKOS
"Impedance of fractal blocking electrodes"
J. Electrochem. Soc. 133 (10) (1986) 2061

Admittance plot for all modifications



Semicircles representing the admittance are depressed with increasing roughness.

FP - Fine polished sample (Mr. Velten, University of Saarland, Germany)

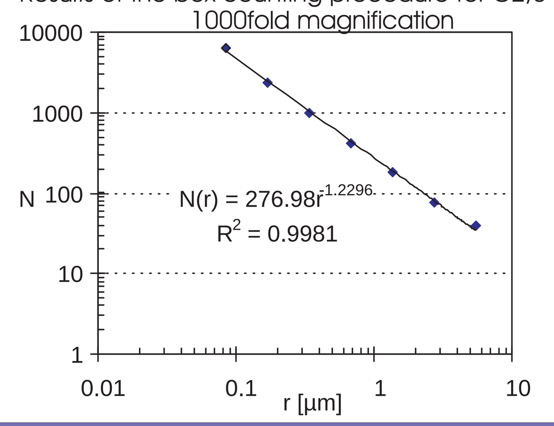
Digital Image Processing (DIP)

For the determination of the fractal dimension D_F cross sections of all surface modifications were made and investigated by SEM in several magnifications (50-,1000-, 500-, 1000-, 5000fold).
The border line of the cross sections was analysed using the box counting algorithm to get the fractal dimension $D_{F,B}$ (Corel Foto Paint, UTHSCSA Imagetool). The slope of the regression line in the plot log(N)=f(log(r)) represents the fractal dimension $D_{F,B}$ for the analysed one dimensional object (border line):

$$N \quad r \qquad const. \quad r^{\quad D_{F,B}}$$

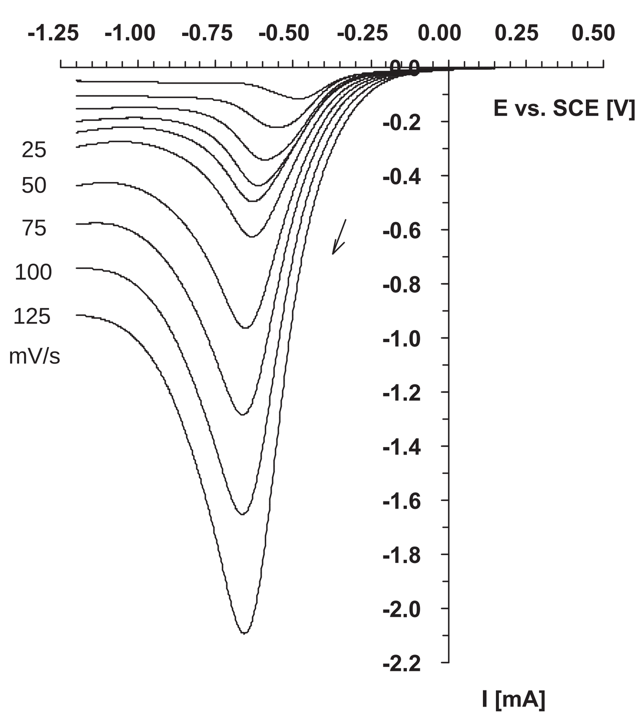
For the transformation into a two dimensional context (surface) $D_{F,B}$ has to be increased by one assuming that the fractal dimension is the same in all directions.

Results of the box counting procedure for C2,5
1000fold magnification



Linear Sweep Voltammetry (LSV)

Electrochemical reduction of ferricyanide
LSV scans with varied scan rates for C2,5

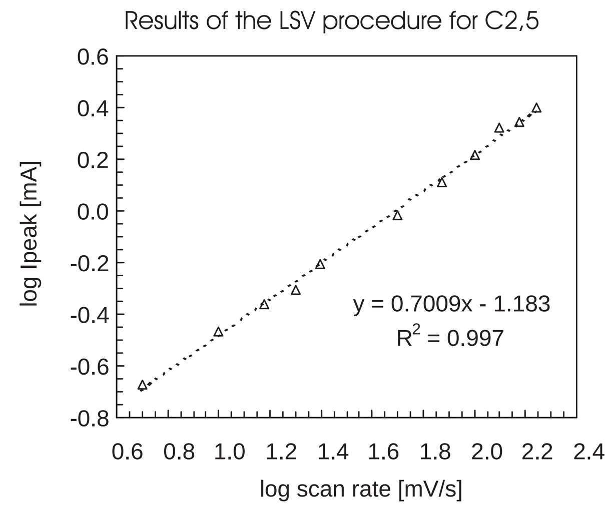


electrolyte: 10 mmol/l ferricyanide $K_3[Fe(CN)_6]$ in 0.5 mol/l Na_2SO_4 as supporting electrolyte, not deaerated at 22 °C
potential scans from +0.2 V (SCE) to -1.2 V (SCE) in cathodic direction with varied scan rates from 1 to 200 mV/s
background correction
measuring system: AUTOLAB
estimation of D_F from slope a of the regression line in the plot log i_{peak} vs. log scanrate:

$$a \quad \frac{D_F \quad 1}{2} \qquad [2]$$

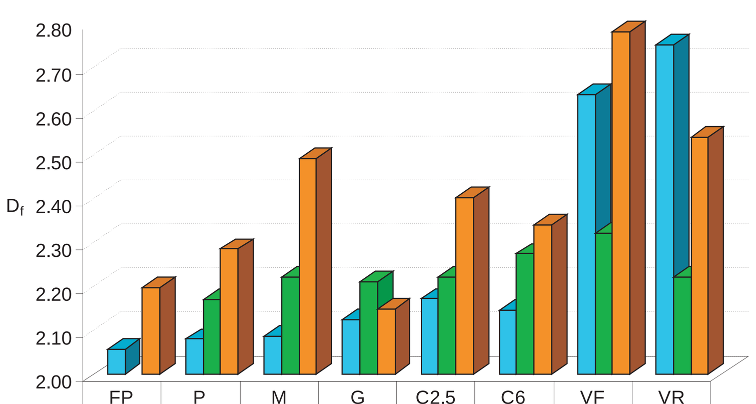
[2] T. PAJKOSSY, L. NYIKOS
"Diffusion to fractal surfaces
III. Linear sweep and cyclic voltammograms"
Electrochim. Acta 34 (2) (1989) 181-186

Results of the LSV procedure for C2,5



Summary

Comparison of the fractal dimension D_F obtained by the 3 different methods



	FP	P	M	G	C2.5	C6	VF	VR
EIS	2.06	2.08	2.09	2.12	2.17	2.14	2.64	2.75
DIP		2.17	2.22	2.21	2.22	2.27	2.32	2.22
LSV	2.20	2.28	2.49	2.15	2.40	2.34	2.78	2.54

With three different methods it is possible to obtain comparable results for the fractal dimension D_F. LSV measurements provide too high values for smooth surfaces. Here a disturbing influence of the passive layer must be taken into account. In contrast to electrochemical methods (integral methods) for DIP only a small fraction of the surface is analysed. This could be a reason for too small values obtained for rough surfaces by DIP.
We propose the use of EIS and LSV as non-destructive and fast methods to get information about the fractal character of metallic surfaces.

Cell biological examinations

M G VR C6 P

D_F values obtained by LSV

2.49 2.15 2.54 2.34 2.28

Fibronectin expression of osteoblastic cells MG-63 on differently structured titanium surfaces after 24 hours:
immunoblotting performed by anti-fibronectin antibody (Sigma)
visualized with chemiluminescence

Fibronectin as a protein of the extracellular matrix was differently expressed in dependence on the surface structure. Rougher surfaces induce a higher expression of fibronectin.
There is a surprisingly good correlation between the fibronectin expression and the physical parameter fractal dimension. This parameter could be an indicator for later cell behaviour and can help in searching for the nature of biocompatibility.

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