

INTRODUCTION

Metallic stents can produce immune reactions that cause restenosis. This effect is mainly due to the release of toxic/allergenic elements from the stent material leading to inflammatory and thrombogenic response. The risk of restenosis can be reduced by covering the stent surface with biocompatible substances that avoid or diminish foreign body reaction. This effect can be attained either with biodegradable and drug eluting polymeric coatings [1] or with thin biocompatible metallic and ceramic layers. These layers act as diffusion barrier and prevent allergenic elements from leaving the stent material.

COATING MODEL (cross section)

The stack coating presented here combines a ceramic coating (TiNbN) serving as diffusion barrier with a calcium phosphate (CaP) envelope. This coating structure is favourable since least irritation of the vessel wall should be obtained, if the stent surface is formed by a substance which is highly similar to body-own material. This property can be provided by calcium phosphates like brushite and hydroxyapatite, the minerals that take part in the formation of bone tissue [2].

According to recent results of Webster et al. [3], surface texture plays an important role during endothelium formation at the stent surface. At different biocompatible materials nanoscale surface textures (< 1 μm) were instantaneously colonized by endothelial cells, effectively masking the foreign surface.

Consequently, by structuring the surface of stents with nanoporous CaP coatings the rapid wrapping of the stent material by endothelium should be encouraged and, therefore, the risk of restenosis can be reduced. Additionally, the nanoporous CaP structure can provide a high wettability for body fluids and can serve as a drug reservoir in order to support the healing process. Furthermore, CaP coatings can be fully resorbed by the human body.

This desired nanoporous structure of the CaP layer should be achieved by a thin SiO₂ xerogel layer between the ceramic coating and the electrochemically deposited CaP layer. Furthermore this layer should enhance the adhesion of the CaP layer.

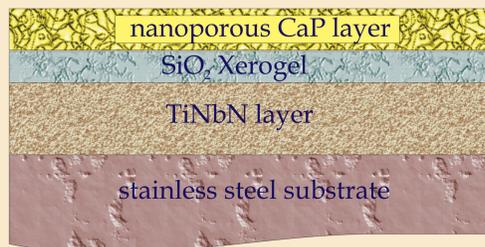


Fig. 1: three layer coating model

MATERIAL AND METHODS

The samples of stainless steel were pre-coated by Physical Vapor Deposition (PVD) with a TiNbN layer of 4 μm thickness. Before the coating process the stainless steel samples were cleaned by acid pickling followed by rinsing with deionised water.

Then the samples were covered with a thin SiO₂ xerogel layer [4]. It was prepared from a diluted TEOS sol (1:150) which was finely dispersed by an ultrasonic nebulizer. During drying the sol film transformed to a xerogel film, the properties of which determined the conditions for the following electrochemical deposition of the CaP coating.

The CaP coating consists of brushite (> 95 wt%) and hydroxyapatite (< 5 wt%) as revealed by XRD and EDX. It was precipitated from an electrolytic bath (diluted between 1:5 and 1:15) with both DC and pulsed DC (varied between 3V and 9V) [5]. The coating time was 15...180 sec.

Investigations of the prepared coating layers were made with SEM (FESEM SUPRA 25, Zeiss, Germany), EDX (X-flash + Quantax, Bruker AXS, Germany) and XPS (Axis Ultra, Kratos, Manchester, GB).

Comparison of CaP coatings with and without SiO₂ xerogel underlay

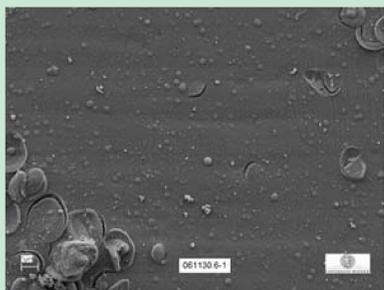


Fig. 2: The CaP coating without SiO₂ xerogel underlay shows a compact structure without pores. At some regions this compact layer is peeling of. (original dimensions 23 μm x 17 μm, scale bar 1 μm, acc. voltage 3 kV)

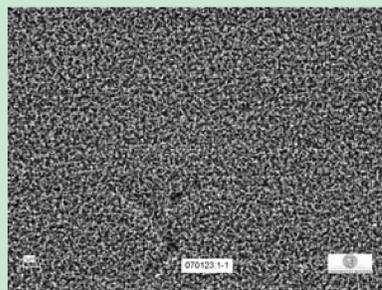


Fig. 3: The CaP coating with SiO₂ xerogel underlay shows the desired highly nanoporous structure which is very uniform. No peeling can be observed. (original dimensions 23 μm x 17 μm, scale bar 1 μm, acc. voltage 3 kV)

Verification of the SiO₂ xerogel layer by SEM and EDX

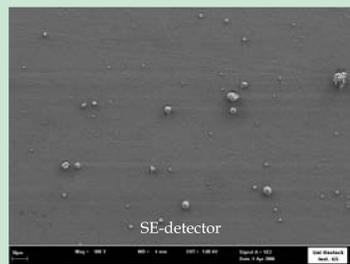


Fig. 4: SiO₂ xerogel layer on titanium substrate (mag. 500x, 1kV, orig. dimensions 227 μm x 171 μm)

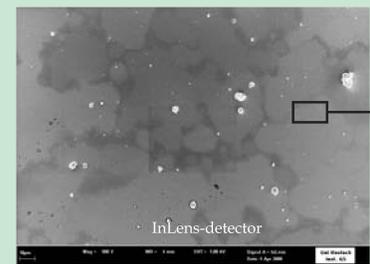


Fig. 5: SiO₂ xerogel layer on titanium substrate (mag. 500x, 1kV, orig. dimensions 227 μm x 171 μm)

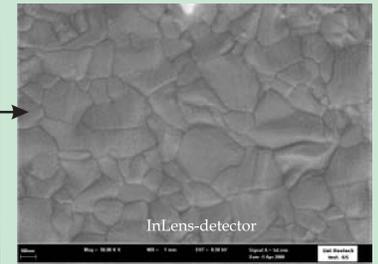


Fig. 6: Region of a bright area in fig. 5 in high magnification (mag. 5000x, 500 V, orig. dimensions 2.27 μm x 1.71 μm), only the structure of titanium is visible.

A direct detection of the SiO₂ xerogel layer by SEM and EDX was difficult because of the lack of sufficient material. With an in-lens-detector at 1kV (beam-voltage) any coating areas on the TiNbN layer were visible (see Fig. 5). It's not a complete covering but rather a meshed layer. Attempts to show the structure of this covering at higher magnification were not successful (see Fig. 6). Also by EDX no Si could be detected.

Verification of the SiO₂ xerogel layer with XPS

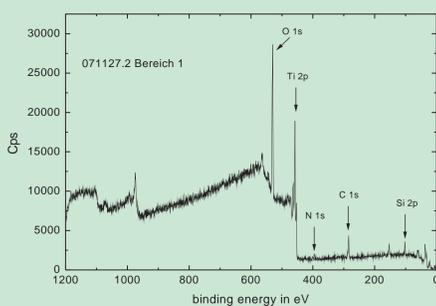


Fig. 7: XPS-spectrum of a sample with Titanium layer and SiO₂-xerogel meshed covering. Both Si and O, Ti, N, C peaks are visible.

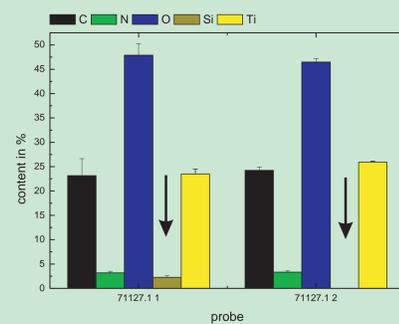
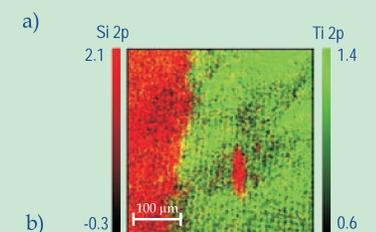
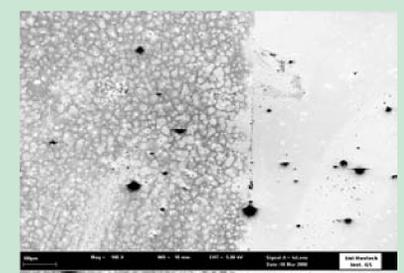


Fig. 8: Element content (at%) at the surfaces of Ti samples with (left group) and without (right group) SiO₂-xerogel coating. In the left group the Si-column (see arrow) shows a content of about 3 at% while in the right group this column is empty. Also the element content of oxygen is higher on the sample with SiO₂-xerogel coating

It was possible to verify the existence of the thin meshed SiO₂ xerogel layer directly only with XPS. Figure 7 shows the XPS-spectrum of the sample region presented in fig. 4-6, respectively, which shows an obvious Si-peak. In fig. 8 the element content of this area is shown (left group) in contrast to that of a reference sample with a Ti layer but without xerogel coating (right group). For this sample no Si could be detected and the element content of oxygen is less than that of the sample with SiO₂ xerogel coating (left group). In fig. 9 a comparison between a SEM picture (InLens-detector) and an XPS mapping of Si and Ti of a transition between regions with (left side) and without SiO₂ xerogel coating is presented. It can be seen a correlation between the area of SiO₂ xerogel coating and the Si detection by XPS.

Fig. 9: Transition between region with (left) and without SiO₂ xerogel layer (right) on a titanium substrate
a) SEM micrograph, mag. 100x, 5kV, InLens detector, orig. dimensions 1140 μm x 855 μm
b) XPS mapping of Si (red) and Ti (green), arbitrary units



CONCLUSIONS AND SUMMARY

The proposed stack coating composed of a TiNbN film plus SiO₂ xerogel layer and an outer nanoporous CaP film offers promising features to overcome the lack of harmless bioactive stent coating that ensure a long-term stent application with reduced risk of restenosis. We could show that the desired nanoporous structure of CaP film and their high adhesive strength is caused by the xerogel underlay. The verification of this underlay was only possible by XPS measurements.

References

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