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Analysis of the In Vivo Oxidation and Integrity of a Zirconium Nitride Multilayer Coated Knee Implant and Possible Effect of Oxidation on the Implant-Cement-Bone Interface Fixation Strength

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Abstract

A ZrN multilayer coated knee implant was retrieved due to early aseptic loosening and showed a greyish coloring instead of its characteristic bright yellow coloring on most of its surface. The first aim of this study was to analyze the surface composition the retrieved implant. Furthermore, as the oxide layer (greyish coloring) might arise the concern of a compromised cement-implant fixation strength, the second aim of this study was to evaluate the implant-cement-bone interface fixation behavior of artificially oxidized ZrN multilayer coated tibial components in an in vitro test set up.

A surface composition analysis via scanning electron microscopy with energy dispersive X-Ray was performed in characteristic parts of the femur component and in the gliding surface. The cement-implant fixation strength was evaluated by means of a push-out test performed in artificially oxidized ZrN multilayer tibial components and the results compared to the cement fixation strength of non-oxidized components.

The surface analysis showed that the grey coloring was due to oxidation of the most superficial surface of the ZrN multilayer, while the rest of the layers kept their integrity. Moreover, bone cement particles where found embedded in the UHMWPE gliding surfaces, which continuously polished the articulation surface of the femur component until the appearance of a transition layer between the ZrN shield layer and the first CrN intermediate layer. No delamination, roughening nor deep scratches in the ZrN multilayer coating were seen. The artificially oxidized ZrN multilayer coated tibial components showed a similar push-out strength (3 025 N ± 239 N) compared to the non-oxidized components (3 014 N ± 166 N).

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In conclusion, the grey coloring seen in the retrieved ZrN multilayer coated implant was due to the superficial oxidation of the ZrN shield layer, having no impact in the underlying layers and demonstrating stability of the coating even under worst-case conditions. Finally, even with an oxidized surface, the ZrN multilayer coated tibial components demonstrated a secure cement fixation.

Keywords: Total knee arthroplasty; Zirconium nitride multilayer; Oxidation; Retrieval analysis; Fixation strength

Introduction

Even though Total Knee Replacement (TKR) is an effective and successful long-term treatment for osteoarthritis, adverse effects due to polyethylene wear or release of metal ions are still a major concern.[1-3] Metal ions, released by the implant component, are suspected to trigger delayed-type hypersensitive reactions, local or systemic adverse effects, activate the immune system or may even contribute to the pathophysiological mechanism of aseptic loosening.[1,4]

The amount of polyethylene wear depends, besides the patient's weight and activities, on the implant design, mainly on the tribology characteristics of the bearing surfaces. The polymer components are most of the time made out of Ultrahigh Molecular Weight Polyethylene (UHMWPE), whereas metal components are made out of Cobalt-Chromium-Molybdenum (CoCrMo) or Titanium Alloys (Ti6Al4V).[5] Improvements in material and sterilization methods led to improved wear properties of the polyethylene components in the last decades.[6-10] On the other hand, modified surfaces on the metal implant side were developed to improve tribological characteristics and reduce metal ion release.[11,12]

Surface modifications have been used in various orthopedic implants for more than 30 years now. Different coating technologies are available for knee implants such as titanium nitride, titanium niobium nitride monolayer coatings or a zirconium nitride multilayer coating.[11,12] Other solutions are surface modification such as oxidized zirconium or full ceramic (alumina or alumina-zirconia) total knee arthroplasties. All of them have the purpose of improving the biocompatibility and tribology of the implants, and especially to avoid or reduce the release of metal ions.[11]

The Zirconium Nitride (ZrN) multilayer coating investigated in this study is composed of 7 layers and produced by a Physical Vapor Deposition (PVD) coating technology. First, a chromium adhesion layer provides a bond between the CoCrMo base material and the subsequent layers. Then, a coating system of 5 intermediate layers is applied, which is made out of alternating Chromium Nitride (CrN) and Chromium Carbon Nitride (CrCN) layers and allows to even out the differences in hardness between the relatively soft chromium adhesion coating and the very hard top coating. The top layer is made of zirconium nitride, a material known for high biocompatibility, low friction and high hardness. The zirconium nitride multilayer coating technology shows good tribology characteristics for wear and reduces metal ion release to the level of detection,[13,14] it is in clinical use since 2006 and shows promising clinical results.[4,15-19]

All implants are exposed to oxidation in the human body,[1,20] and oxidation may also occur in environments exposed to oxygen prior to implantation, for example within packaging during storage. This oxidation process leads to a thin oxide layer on the surface of implants, which is usually 3 nm - 4 nm thick, is stable at this thickness and prevents further oxidation.[21,22] This oxidation of ZrN multilayer coated implants can lead to color changes in the surface from golden to grey,[23] which may arise concerns to the surgeon before an implantation or during a revision surgery. Furthermore, it is unknown if the oxidation on the backside of the implants has an influence on the implant-cement-bone interface fixation strength in comparison to non-oxidated implants.

The purpose of this study was to analyze the oxidation degree and the surface composition of a retrieved ZrN multilayer coated TKR femur component and its corresponding gliding surface. Additionally, in order to clear the question if the oxide layer of the ZrN multilayer coating might influence the implant-cement-bone interface fixation strength, a push-out test was performed on new and artificially oxidized ZrN multilayer coated tibial components.

Materials and Methods

Implant and clinical data

A ZrN multilayer coated knee implant was retrieved after 2 years in situ due to early aseptic loosening from a 72 years old male patient having a 102 kg weight (Figure 1). The following components were retrieved: AS VEGA System® PS Femur Component (size F6R), AS VEGA System® Tibia Component (size T5), and VEGA System® PS Gliding Surface (size T5; 10 mm) (Aesculap AG, Tuttlingen, Germany). Femur and tibial component were cemented using Palacos R+G bone cement (Heraeus Medical GmbH, Wehrheim, Germany). During revision surgery, the medial tibial plateau looked necrotic without any bleeding and there were many bone cement particles in the joint.

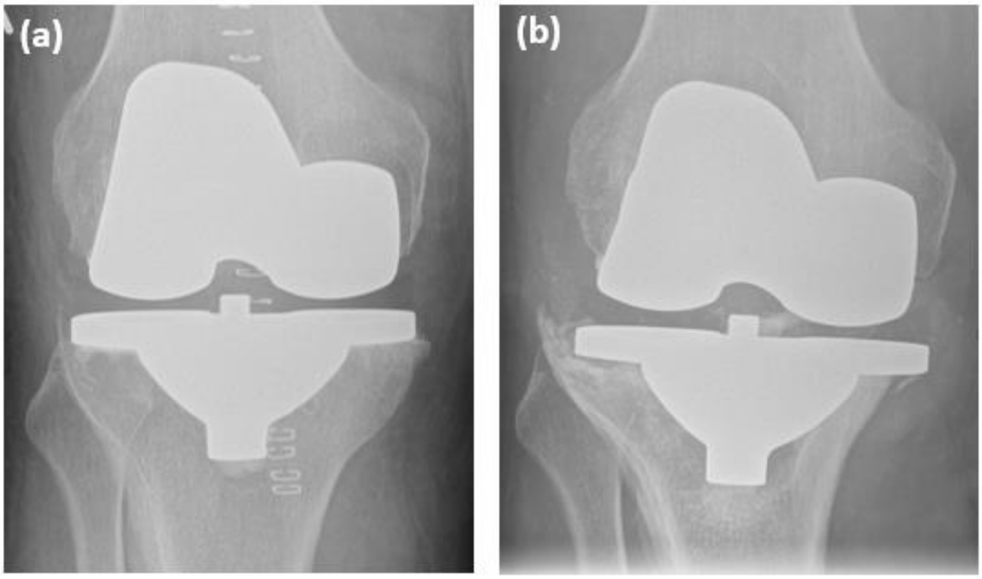

Figure 1: Anteroposterior views of the knee (a) immediately after surgery and (b) 21 months later, demonstrating the collapse of the medial tibial plateau and the loosening of the tibia.

Surface characterization of retrieved implant

After removal, the implant components were immediately rinsed with saline solution and shipped for further analysis. The metallic components were then gamma sterilized two times with 30 kGy and cleaned in an ultrasonic bath with ethanol for 30 minutes, whereas the polyethylene gliding surface was washed in an ultrasonic bath with two mild detergents (Helizyme® and Helipur®, B. Braun, Melsungen, Germany) for a total of one and a half hours each, submerged in 37 % HCl for 30 minutes and finally rinsed with distilled water.

A calo tester (Kalottchen / L, Ceme Coat GmbH, Aachen, Germany) was used in order to create ball craters and visualize the multilayer structure in two representative areas of the femur component, which had two different colors (the patellar flange surface was grey and the articulation surface of the condyles was yellow). For the creation of these craters, a steel sphere rotated against the femur component surface for 3 minutes, whilst diamond paste was applied to the contact area.

Overview images of the femur (Figure 2) and gliding surface (Figure 3) were taken with a digital microscope (VHX-5000, Keyence Corporation, Osaka, Japan) and representative areas were selected for their composition analysis through Scanning Electron Microscopy (SEM) (EVO 50, Carl Zeiss AG, Oberkochen, Germany) with Energy Dispersive X Ray (EDX) (X-Max, Oxford Instruments plc, Abingdon, United Kingdom). Roughness measurements (HOMMEL-ETAMIC TURBO WAVE V7.32, JENOPTIK Industrial Metrology Germany GmbH, Villingen-Schwenningen, Germany) were performed at the articulating surfaces of the femur component based on the ISO 7207-2:2011/Amd.2:2020. Three measurements were performed at the lateral condyle, three at the medial condyle and three at the patellar flange (Figure 2, red lines).

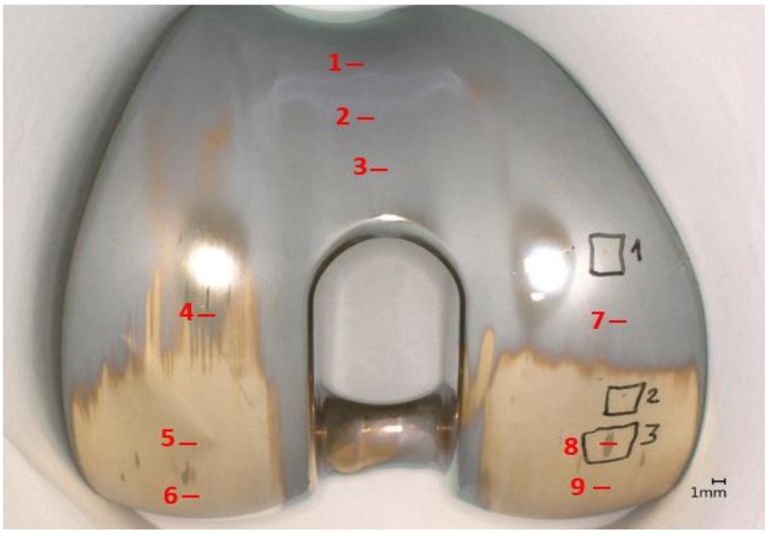

Figure 2: Retrieved ZrN multilayer coated femur component with representative areas selected for SEM/EDX analysis (black squares). Inside the squares 1 and 2 are the two ball craters created with the calo tester. The roughness measurement points are marked in red.

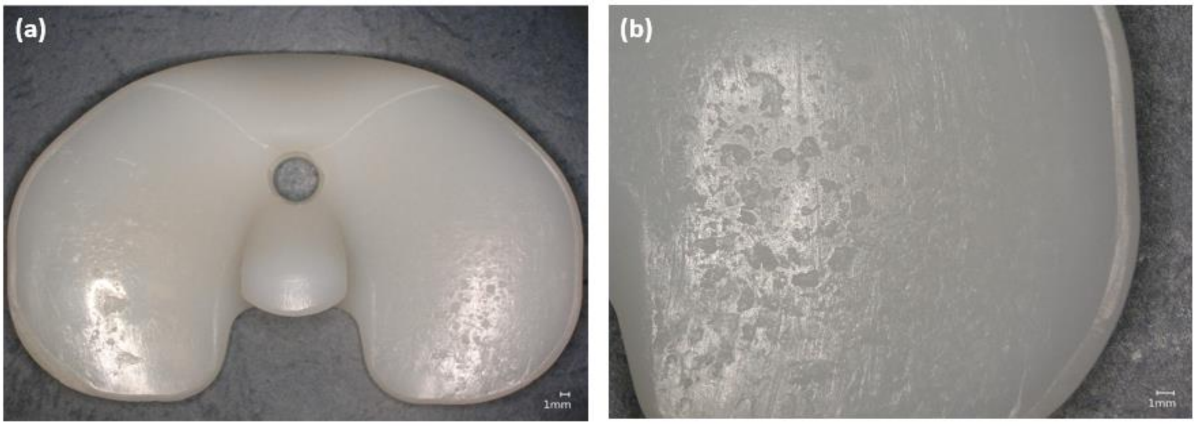

Figure 3: (a) Overview of the retrieved gliding surface. Both sides show impressions generated by third body particles. (b) Overview of the lateral side of the retrieved gliding surface.

Push-out test on artificially oxidized tibial components

With the purpose of measuring the implant fixation strength after cementation of oxidized ZrN multilayer coated tibial trays, a push-out test based on Grupp et al. [24] was performed. The smallest tibial tray size of the AS VEGA System® (size 0) (Aesculap, Tuttlingen, Germany) with the ZrN multilayer coating was selected, as it provides the least surface area for fixation. Two testing groups were defined: new (ZrN new, n = 6) and oxidized (ZrN ox, n = 6).

In order to know how much the tibial trays should be oxidized, the surface composition at the proximal side of an AS EnduRo (Aesculap, Tuttlingen, Germany) tibial retrieval, oxidized over the entire surface, with an in situ time of 5 years (R63 from Schierjott et al. [25]) was analyzed by means of SEM/EDX. The analysis showed an oxygen content of 26 wt%. The artificial oxidation was performed by submerging the ZrN multilayer coated tibial trays in a closed bottle containing 0.9% NaCl solution. The bottle was then placed in an oven (Binder FP400, Binder GmbH, Tuttlingen, Germany) at 90°C for a total of 9 days. The SEM/EDX analysis showed an average oxygen content between 24 wt% and 27 wt% at the proximal side of the artificially oxidized ZrN tibias and a color change similar to the one seen in the retrieval (Figure 4).

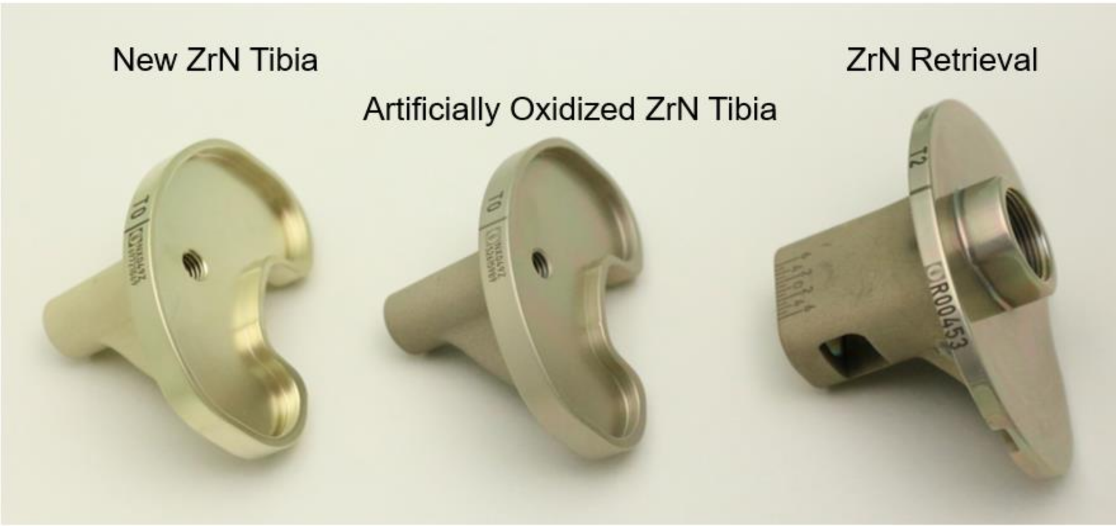

Figure 4: Color change comparison between a new out of the box ZrN tibial component, an artificially oxidized ZrN tibial component and a ZrN retrieval with surface oxidation.

For the cementation procedure, polyurethane foam blocks (20 pcf cellular rigid foam, Sawbones®, Malmoe, Sweden) were machined with a cavity for the distal part of the tibial component with a gap of at least 1 mm. Moreover, a continuous hole through the entire block was prepared in order to provide an opening for the appliance of the load during the push-out test. The tibial tray, bone cement (Palacos® R, Heraeus Medical GmbH, Wehrheim, Germany) and vacuum mixing system (Easymix® uno, Osartis GmbH, Dieburg, Germany) were stored in an air conditioned laboratory (19°C) for at least 24 hours prior testing.

The cementation procedure was performed at the midterm of the application window recommended by the bone cement manufacturer (between 2:30 min and 3:10 min) and the implanted tibial component was kept under a controlled pressurization of 100 N. After bone cement hardening, the polyurethane foam blocks with the cemented tibial components were stored upside-down in a 0.9% NaCl solution for 48 hours at 37°C (Binder ED400 + RS422, Binder GmbH, Tuttlingen, Germany).

After 48 hours, a push-out test was carried out on the cemented tibial components. The load was applied to the distal tip of the tibial component via a screw and a steel ball in order to avoid constraining forces and to obtain a pure push-out load. The test was performed with a preload of 20 N and a test speed of 5 mm/min using a quasi-static testing machine (Zwick Z010, Zwick Roell, Ulm, Germany). A summary of all the analysis performed is shown in Figure 5.

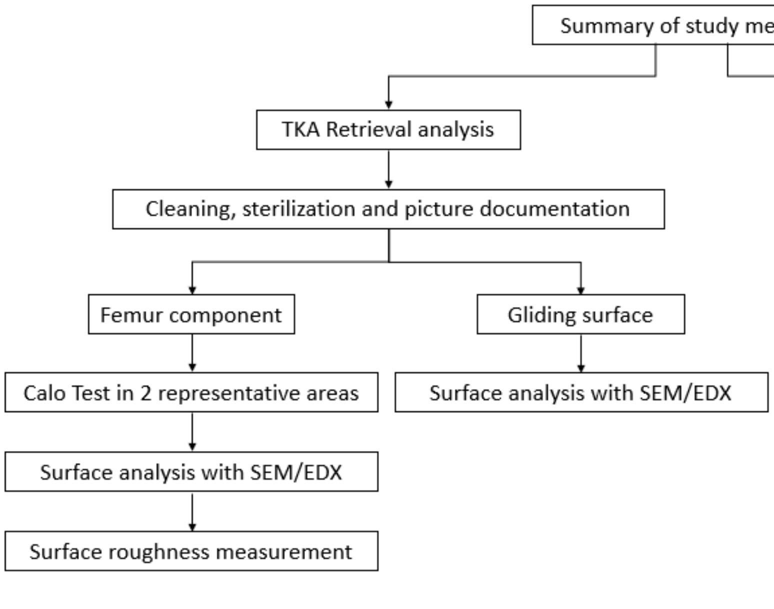

Figure 5: Summary of the analysis performed in the study.

Results

Surface characterization of the retrieved implant

The roughness measurements of the articulating lateral and medial condyles were between 0.01 µm and 0.02 µm, whereas the roughness at the patellar flange was between 0.02 µm and 0.04 µm.

The overview pictures of the ball craters taken with the digital microscope clearly show the different layers of the ZrN multilayer coating (Figure 6 and Figure 8). Several points were selected across the multilayer surface in order to analyze its composition with EDX (Figure 7 and Figure 9) and their spectrums are shown in Table 1 and Table 2.

The SEM/EDX analysis showed oxidation of the femoral surface on the grey areas. In general, the higher the oxygen detected, the smaller was the nitrogen signal. Localized areas at the articulation surface, where the transition zone between the shielding ZrN final layer and the first of five intermediate layers of CrN and CrCN appeared, were detected (Area 3 in Figure 2). This was demonstrated by the EDX analysis, which showed a combination of Zr and Cr content with varying degrees in this localized areas (Figure 10 and Table 3).

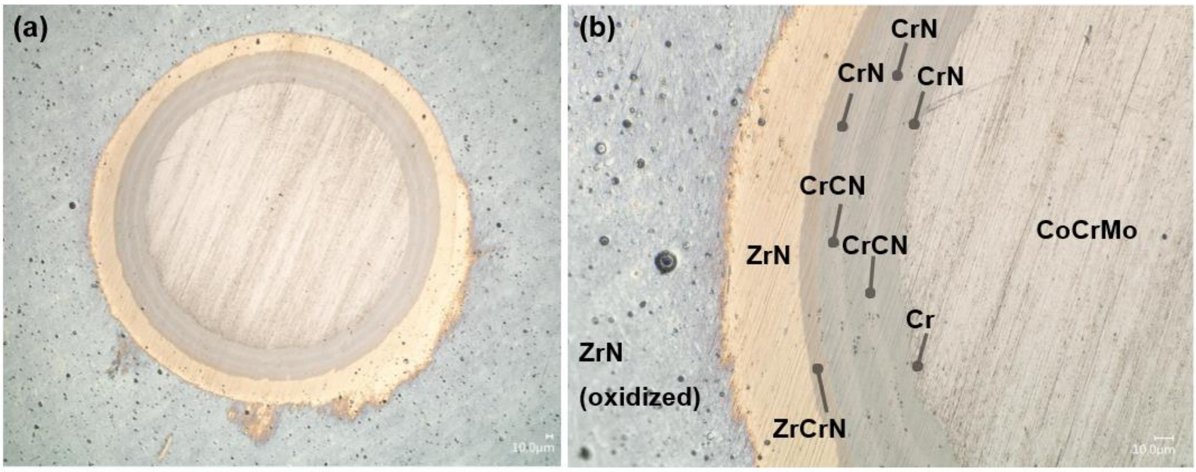

Figure 6: (a) Overview of the ball crater made at the grey surface of the femur component (Area 1 in Figure 2). (b) Magnification of structure of the multilayer coating, which consists of a thin adhesive Cr bond layer, five alternating intermediate layers out of CrN (dark grey layers) and CrCN (light grey layers), a transition layer out ZrCrN (brown layer) and a final ZrN shielding layer (yellow layer). The most superficial surface of the ZrN shows oxidation, seen as a grey color.

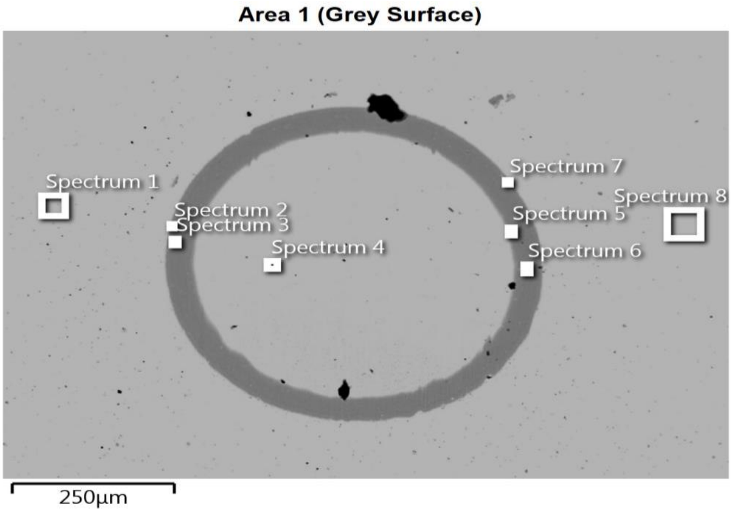

Figure 7: BSD image with points selected for EDX analysis from the ball crater at the medial condyle grey surface of the ZrN multilayer coated femur retrieval (Area 1 in Figure 2).

Table 1: Spectrums from the points selected on Figure 7 from the ball crater at the medial condyle grey surface of the ZrN multilayer coated femur retrieval (Area 1 in Figure 2).

Spectrum Name	Element in wt%									
	C	N	O	Si	Cr	Mn	Co	Zr	Mo	Total
Spectrum 1 (ZrN oxidized)	12.19	4.87	10.39	-	0.54	-	-	72	-	100
Spectrum 2 (CrN or CrCN)	3.81	10.7	-	-	83.19	-	-	2.3	-	100
Spectrum 3 (CrN or CrCN)	5.63	10.73	-	-	83.64	-	-	-	-	100
Spectrum 4 (CoCrMo)	6.22	-	-	0.67	27.16	0.72	60.69	-	4.54	100
Spectrum 5 (CrN or CrCN)	3.97	14.2	-	-	70.4	-	9.8	0.59	1.03	100
Spectrum 6 (CrN or CrCN)	4.83	13.22	-	-	80.78	-	0.73	0.43	-	100
Spectrum 7 (CrN or CrCN)	4.27	13.36	-	-	80.67	-	0.57	1.13	-	100
Spectrum 8 (ZrN oxidized)	13.5	3.54	10.41	-	0.52	-	-	72.03	-	100

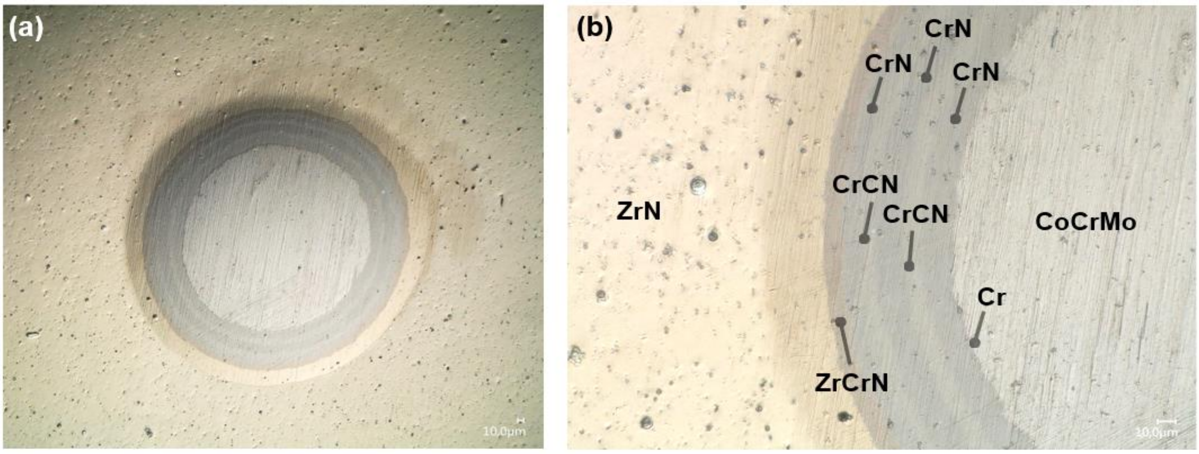

Figure 8: (a) Overview of the ball crater made at the articulation surface (Area 2 in Figure 2). (b) Magnification of structure of the multilayer coating, which consists of a thin adhesive Cr bond layer, five alternating intermediate layers out of CrN (dark grey layer) and CrCN (light grey layer), a transition layer out ZrCrN (brown layer) and a final ZrN shielding layer (yellow layer).

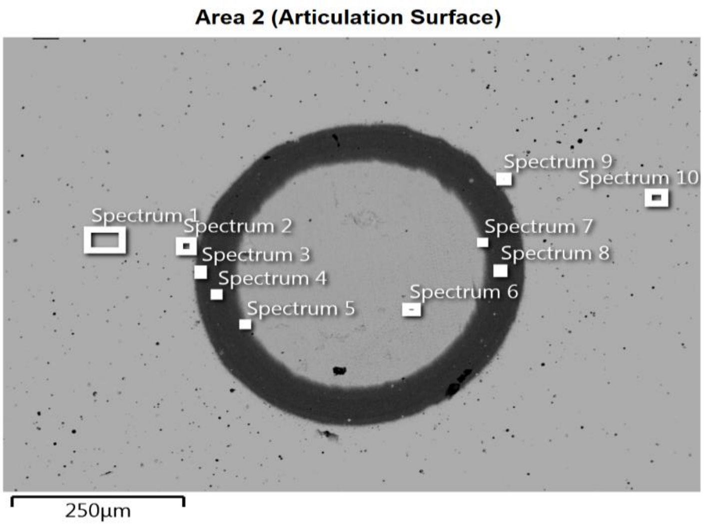

Figure 9: BSD image with points selected for EDX analysis from the ball crater at the articulation surface of the ZrN multilayer coated femur retrieval (Area 2 in Figure 2).

Table 2: Spectrums of the points selected on Figure 9 from the Area 2 of the ZrN multilayer coated femur retrieval. The different layers as well as the substrate material could be identified.

Spectrum Name	Element in wt%									
	C	N	O	Si	Cr	Mn	Co	Zr	Mo	Total
Spectrum 1 (ZrN)	11.14	6.86	1.08	-	0.67	-	-	80.25	-	100
Spectrum 2 (ZrCrN)	7.42	6.31	-	-	14.02	-	-	71.69	-	100
Spectrum 3 (CrN or CrCN)	2.28	8.8	-	-	88.93	-	-	-	-	100
Spectrum 4 (CrN or CrCN)	2.12	9.73	-	-	87.61	-	0.53	-	-	100
Spectrum 5 (CrN or CrCN)	2.32	9.72	-	0.2	56.94	-	27.66	0.57	2.59	100
Spectrum 6 (CoCrMo)	4.41	-	-	0.65	28.16	0.67	61.7	-	4.43	100
Spectrum 7 (CrN or CrCN)	2.82	9.91	-	0.29	49.54	-	33.87	0.59	2.98	100
Spectrum 8 (CrN or CrCN)	4.35	9.45	-	-	84.87	-	0.85	0.48	-	100
Spectrum 9 (ZrCrN)	7.23	7.38	-	-	30.52	-	-	54.87	-	100
Spectrum 10 (ZrN)	9.73	6.33	1.19	-	0.59	-	-	82.16	-	100

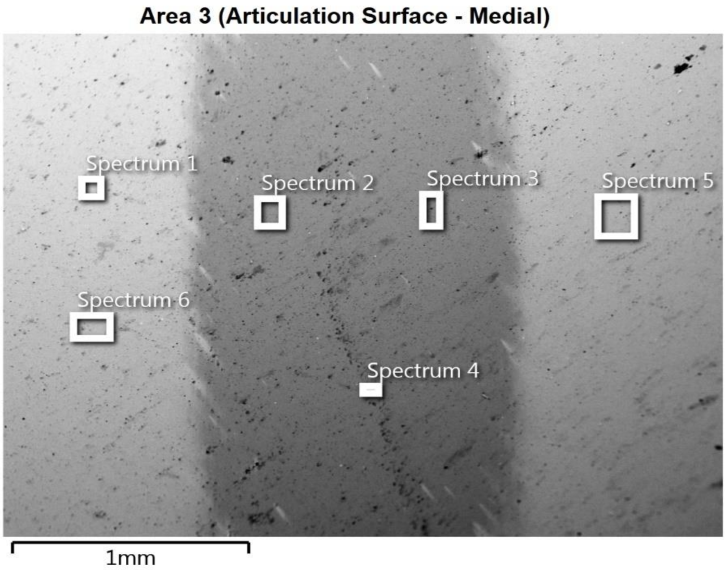

Figure 10: BSD image with points selected for EDX analysis from the Area 3 of the ZrN multilayer coated femur retrieval.

Table 3: Spectrums of the points selected on Figure 10 from the Area 3 of the ZrN multilayer coated femur retrieval. The transition zone between the ZrN shield layer and the first intermediate CrN layer was detected.

Spectrum Name	Element in wt%					
	C	N	O	Cr	Zr	Total
Spectrum 1 (ZrN)	12.64	7.12	1.53	2.44	76.26	100
Spectrum 2 (ZrCrN)	9.56	8.6	-	34.75	47.1	100
Spectrum 3 (ZrCrN)	9.09	7.85	0.6	35.39	47.06	100
Spectrum 4 (ZrCrN)	19.25	7.08	0.78	31.29	41.59	100
Spectrum 5 (ZrN)	10.51	6.97	1.44	2.05	79.03	100
Spectrum 6 (ZrN)	12.79	7.48	1.39	3.53	74.81	100

The UHMWPE gliding surface showed impressions (pits) at the articulation surfaces (Figure 3) generated by third body particles.[26-28] The SEM/EDX analysis showed the presence of particles containing Zr and O inside these impressions (Figure 11 and Table 4), which could have their origin in the contrast medium (ZrO_2) of the bone cement. The presence of these third body particles may had worn out the ZrN shielding layer due to polishing, leading to the appearance in a very localized area at the articulation surface of the ZrCrN transition layer.

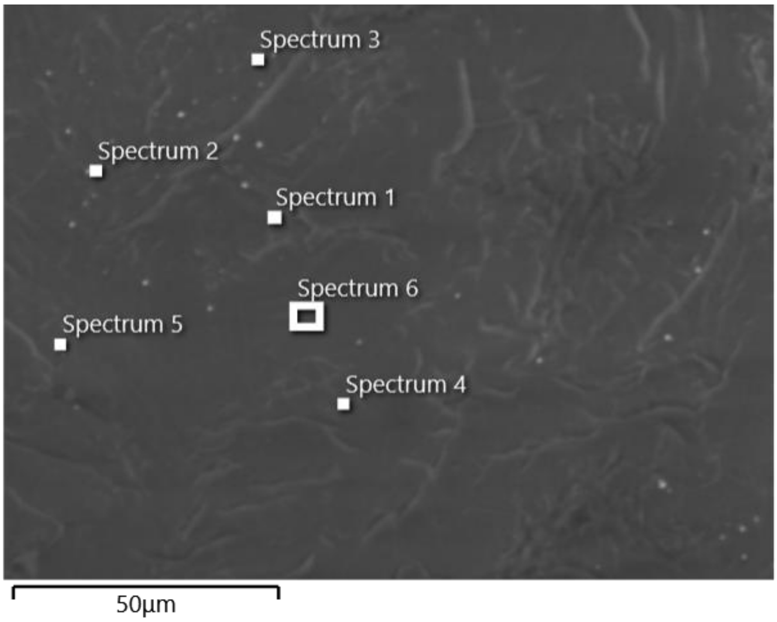

Figure 11: BSD image with points selected for EDX analysis from lateral side of the retrieved gliding surface.

Table 4: Spectrums of the points selected on Figure 11 from the lateral side of the retrieved gliding surface. Particles containing Zr and O were found.

Spectrum Name	Element in wt%			
	C	O	Zr	Total
Spectrum 1	90.18	2.48	7.34	100
Spectrum 2	92.06	1.87	6.06	100
Spectrum 3	96.43	1.05	2.52	100
Spectrum 4	91.39	1.83	6.77	100
Spectrum 5	91.9	1.23	6.87	100
Spectrum 6 (Background)	100	N/A	N/A	100

Push-out test on artificially oxidized tibial components

The push-out strength of artificially oxidized ZrN tibial components was 3 025 N ± 239 N, whereas for the unoxidized ZrN tibia components 3 014 N ± 166 N (Figure 12). No significant differences were seen. In all the tested samples, failure occurred at the interface between the Sawbones® and bone cement (Figure 13).

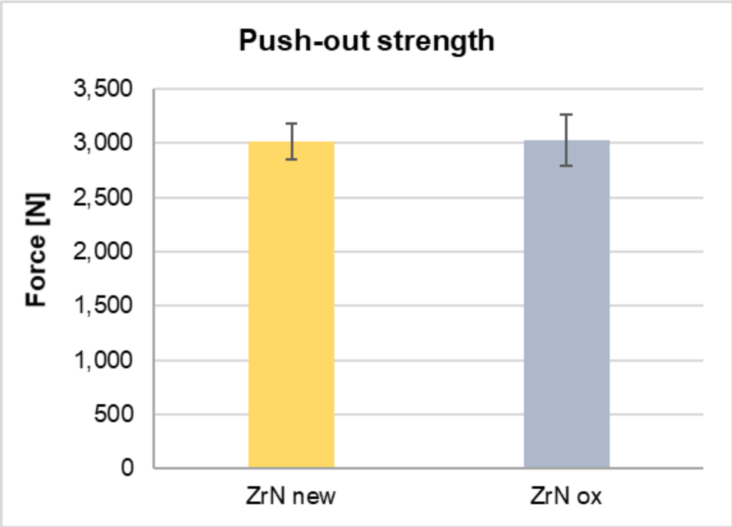

Figure 12: Push-out strength of the ZrN new and ZrN ox groups. No significant differences were seen.

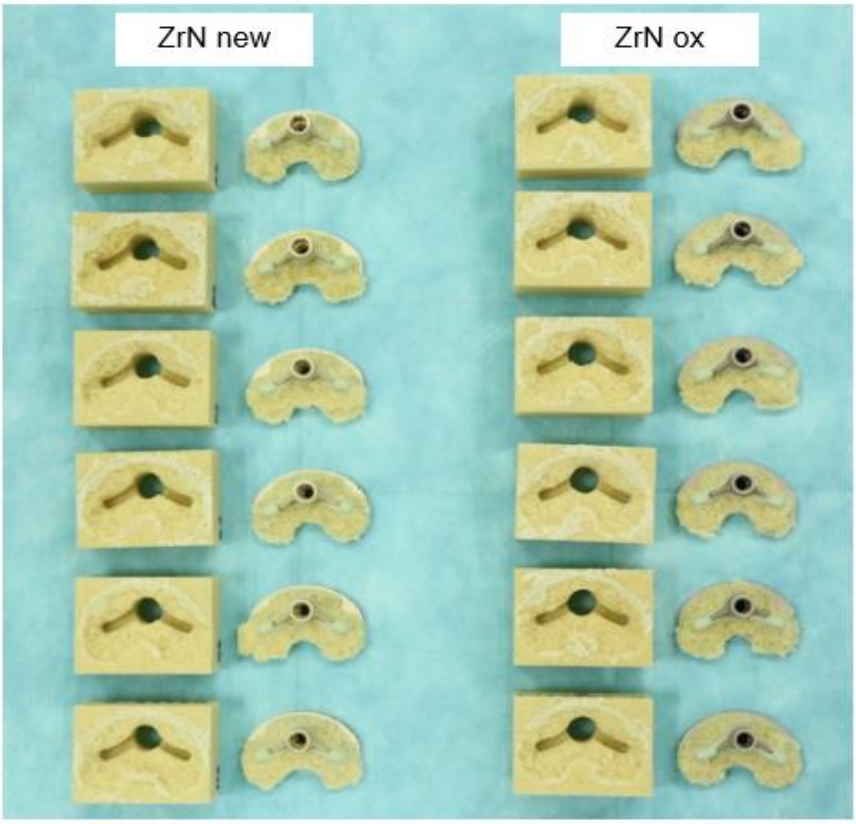

Figure 13: After the push-out test, failure occurred at the bone cement-foam block interface in all the tested samples of the ZrN new and ZrN ox groups.

Discussion

The aim of this study was to analyze by means of a SEM/EDX the surface composition of a retrieved ZrN multilayer coated femur component and its gliding surface, as well as to evaluate the implant-cement-bone interface fixation behavior of artificially oxidized ZrN multilayer coated tibial components in an in vitro test set up. This is the first study to perform a detailed surface composition analysis on a retrieved ZrN multilayer coated implant.

Oxidation of the ZrN multilayer coating

At the time of a TKR revision surgery due to an early aseptic loosening, it was observed that most of the surface of the ZrN multilayer coated components had a greyish coloring instead of its characteristic gold coloring, which was only seen at the direct condylar articulation surface of the femur component with the UHMWPE component. The EDX analysis performed at the grey surfaces of the ZrN multilayer coated femur showed oxidation of the most superficial layer. Moreover, this oxidation layer might only have some nanometers of thickness, as the ball crater image showed that the grey coloring was only superficial, while the rest of the ZrN layer thickness remained in golden color. The rest of the intermediate layers remained intact. A positive effect of the oxide layer is protection from further corrosion. An exact measurement of the oxidation thickness was not possible with the available equipment due to the curvature of the femoral condyles. However, studies on PVD coatings have demonstrated that the oxidation layer is only a couple of nm thick.[21,22] In a comparison with other PVD coatings, ZrN showed the best corrosion resistance among all tested coatings.[29]

Oxidation of the ZrN multilayer coating is a normal behavior, as every metal in contact with biological systems will undergo a process of bio-corrosion,[1,3,30] and has been reported on in vitro studies before.[14] During the oxidation process, oxygen ions are exchanged by the nitrogen ions of the ZrN layer, demonstrated in the EDX analysis performed on the grey surfaces in comparison with the gold surfaces (Table 1). Besides, this oxidation is clearly visible in the ZrN layer due to the fact that the color of zirconium alloys varies depending on the amount of oxygen and nitrogen they contain.[21,22,31-36] Future studies of the ZrN multilayer coating should be focused on understanding its tribo-oxidation mechanisms by performing a microstructural characterization with more advanced techniques, such as atom probe tomography.

Mechanical stability of the ZrN multilayer coating

The absence of oxidation at the direct articulation surface of the femur component with the UHMWPE component might be due to the constant motion and wear between both components, which did not allow an oxidation film to be formed. Furthermore, the presence of pits at the surface of the UHMWPE gliding surface as well as embedded ZrO_2 particles showed the presence of third body particles from the bone cement, which created a severe abrasive environment. As a result, the articulation surface of the ZrN multilayer coated femur component underwent a constant polishing of its surface through the third body contamination and, in some localized points, the ZrCrN transition layer started to appear (area 3 of Figure 2 and Table 3). However, no delamination, flaking, roughening, deep scratches nor complete worn out of coating were seen, as no significant signal of all the base materials (Co, Cr, Mo) together with a complete disappearance of zirconium was detected.

Moreover, the roughness measurements performed at the articulating surfaces of the femoral condyles demonstrated that the surface was still polished, with roughness values between 0.01 µm and 0.02 µm. This demonstrates the stability of the coating even under worst-case conditions with bone cement third body particles. This is consistent with in vitro studies which have already demonstrated the integrity of the ion release barrier function of the ZrN multilayer coating under severe conditions such as highly demanding activities,[14] and third body contamination.[13] In contrast, in vitro and retrieval studies have shown that CoCrMo implants are prone to present scratches at their articulating surfaces, even without third-body contamination, with roughness values increasing above 0.1 µm.[14,37-39] On the other hand, retrieval studies using alternative monolayer coatings and materials have shown scratches and delamination.[40-43]

Implant-cement-bone fixation strength of oxidized ZrN multilayer coated tibias

In order to clear the final question regarding the influence of the oxide layer of the ZrN multilayer coating to the bone cement fixation strength, a push-out test based on Grupp et al. [24] was performed. The implant-cement-bone fixation strength of oxidized ZrN multilayer coated tibias against non-oxidized ZrN multilayer coated tibias was compared and the results showed that the oxidation of the ZrN multilayer coating did not affect the fixation strength and were in the same range of previously published results with ZrN multilayer coated and uncoated tibia implant of the same design.[24] A limitation of this test was the cementation of the tibial components in artificial bone. However, this was required in order to get reproducible results using a standardized material. Moreover, this method has been able to detect differences in the fixation strength when comparing different designs and procedures.[24,44]

Clinical results of the ZrN multilayer coating

Regarding its clinical outcomes, the National Joint Registry of England, Wales, Northern Ireland & Isle of Man (18) reported a survivorship at 5 years of 97.69% for the ZrN multilayer coated AS Columbus® implant, which is comparable to the results of its uncoated version (97.73%) and the average of all reported TKAs (97.77%). It is important to notice that, according to the register, younger patients received a ZrN multilayer coated implant (average 65 years) in comparison to its uncoated version and to the rest of the TKAs (average 70 years). This might have even created a bias against the ZrN multilayer coated implant, as younger patients have a higher risk of undergoing a revision surgery.[17]

The Australian Orthopedic Association National Joint Replacement Registry annual report 2021 distinguished the revision rates for alternate ceramic surface femoral components in comparison to CoCrMo.[17] The authors reported for the ZrN multilayer coating at 5 years a favorable revision rate of 2.1 (CI 1.5-2.9) in comparison to CoCrMo with 3.1 (CI 3.1-3.2), Oxinium with 4.5 (CI 4.3-4.7) and TiN monolayer coatings with 5.0 (CI 4.4-5.7). Finally, the German Arthroplasty Registry (EPRD, Endoprothesenregister Deutschland) demonstrated overall higher revision rates for coated TKAs in comparison to uncoated TKAs.[45] However, in a detailed analysis, it was demonstrated that ZrN multilayer coated implants had similar revision rates when compared to similar non-coated implants.[15,19]

Conclusion

This was the first study to perform a detailed surface composition analysis on a retrieved ZrN multilayer coated implant and demonstrated that the grey coloring seen in the retrieved ZrN multilayer coated implant was due to the superficial oxidation of the last ZrN layer, with no impact in the underlying layers. No delamination, flaking, roughening, deep scratches nor complete worn out of the ZrN multilayer coating were seen, even under the severe third body particle condition. Finally, the artificially oxidized ZrN multilayer coated tibial components showed a similar cement fixation strength in an in vitro test set-up compared with non-oxidized components, demonstrating a secure cement fixation, even with an oxidized surface.

Conflict of Interest

Three of the authors (Ana Laura Puente Reyna, Brigitte Altermann, and Thomas M. Grupp) are employees of Aesculap AG, Tuttlingen, a manufacturer of orthopedic implants. Jörg Lützner has received research grants and honoraria for lectures from Aesculap AG.

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