Discerning in-vivo corrosion mechanisms and failure modes of explanted prostheses – Part I

By Norman Munroe, Vishal Musaramthota, Christopher Emerson and Kinzy Jones

Introduction
Orthopedic implants have seen a major increase in usage within the US and worldwide. Three decades ago, the average age for a hip replacement was 78 years, while today it is 59 years. The American Academy of Orthopedic Surgeons notes that more than 700,000 primary total hip or knee replacements were performed in the US, with demand doubling in the next decade. However, increased usage has been accompanied by an increase in revision, where the prosthesis is removed. Most joint replacements have been performed primarily on older patients and as such, there is a dearth of information on how these implants would hold up in younger patients over longer periods of time. Despite the advent of new designs and advanced materials, orthopedic surgeons are still concerned that younger knee replacement patients, for example, may need to have replacement in as little as 5 to 10 years, which leads to bone loss every time the surgery is performed.

Figure 1: (a) Diseased hip before and after artificial hip joint implantation [1]; (b) artificial knee joint coated with various ‘Medthin’ coatings from Ionbond that prevent corrosion, minimize wear, offer excellent load carrying capacity and greatly reduce metallic ion concentrations [2]; (c) from left to right, medial-posterior aspect of the a tapered stem region (left) and the inner medial (middle) and lateral halves (right) of the cut sleeve [3].
Significance
There has been an increase in the recall of prosthetic devices (Zimmer – 11,658 in 2015 and DePuy – 40,000 in 2011) based on increased failure rates due to materials defects or construction technology. The FDA in 2015 indicated that tribological interactions (metal on metal) of implants provide a unique risk due to the deleterious effect of metallic debris on surrounding tissues. This research is focused on utilizing a group of explanted hip prostheses of known medical history and develop protocols, from which information can be garnered on microstructure, fretting/crevice corrosion, failure analysis and their manifestations in product design.

Previous research
The following table summarizes some of our previous/current investigations on the biocompatibility of Ti alloys and Mg based biodegradable alloys used for the manufacture of prosthetic and cardiovascular devices. The following alloys are investigated: titanium alloys (NiTi-X, Ti-Ta and Porous Nitinol (PNT)); biodegradable magnesium alloys (Mg-Zn-X); and metal matrix composites (MMC).

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Manufacturing Techniques</th>
<th>Reference of Articles Published</th>
<th>Industrial/University Collaborators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti-Ta-X</td>
<td>Powder Metallurgy, ARC Melting</td>
<td>[4], [5]</td>
<td>Dynamite Technology; National Institute of Standards and Technology (NIST); Electrobright</td>
</tr>
<tr>
<td>PNT</td>
<td>Self-propagating high-temperature synthesis</td>
<td>[6], [7], [8], [9], [10], [11], [12]</td>
<td>Biothrex; Electrobright</td>
</tr>
<tr>
<td>Mg-Zn-X (Biodegradable)</td>
<td>Casting</td>
<td>[13], [24], [27]</td>
<td>ACI Alloys, Inc.; Electrobright; Brunel University, London</td>
</tr>
</tbody>
</table>
Alloy | Manufacturing Techniques | Reference of Articles Published | Industrial/University Collaborators
---|---|---|---
NiTi-X | ARC Melting | [14], [15], [16], [17], [18], [19], [20], [23], [25], [26] | National Institute of Standards and Technology (NIST); Electrobright
NiTi-CNT | Powder Metallurgy | [21], [22] | Fraunhofer Institute, Germany

The results of cyclic polarization corrosion studies on electropolished (EP), magnetoelectropolished (MEP) and porous Nitinol (PNT) are summarized in fig. 2a; potentiodynamic polarization studies on Mg alloys are illustrated in fig. 2b; and EIS polarization resistance due to the growth of osteoblast cells on TiTa alloy are shown in fig. 2c.

*Figure 2: (a) Cyclic polarization scan, where Eb – Break down potential, Er – Rest potential, Subscripts: 1- Untreated PNT, 2- MEP PNT, 3- EP PNT; (b) Potentiodynamic scan; (c) Observation of growth of osteoblast cells on TiTa after inoculation by EIS.*

Fig. 3 (a) illustrates the cytotoxicity of surface treated PNT corrosion products on human osteoblast cells and fig. 3 (b) shows osteoblast cell growth on the surface of various biomaterials.
Fig. 4 illustrates X-ray photoelectron spectroscopy (XPS) analysis to evaluate the surface chemistry of PNT; fig. 4 (a) shows the presence of a passivating titanium oxide surface layer that is void of any nickel oxide. The elemental depth profile and binding energy of atomic species are shown in fig. 4 (b and c).

Current Research
In this investigation, 48 CoCrMo explanted arthroplasty samples were provided by Dr. Carlos Lavernia, Head of Mercy Hospitals Orthopedic Institute. Although the medical history of the explanted prostheses have been documented under strict confidentiality, the processing history of the materials of construction was unknown. Additionally, different design features of varying dimensions are known to introduce microstructural heterogeneity resulting in unpredictable electrochemical, tribological and osseointegration properties. However, discussions on influential factors such as material processing, the resulting microstructure, design of the prostheses, length of implantation as they relate to the appearance of the samples, and the extent to which wear debris is generated at the stem-sleeve interface will be described in future publications.
A micro corrosion cell shown in fig. 5a was employed to conduct corrosion tests on as-cast CoCrMo alloy (AC), low carbon wrought (LCW) CoCrMo alloy and high carbon wrought (HCW) CoCrMo alloy (the composition and types of alloy were ascertained by conducting SEM/EDS analyses and comparing the results with those in the literature). Potentiodynamic polarization tests were conducted in accordance with ASTM F2129-08 using a Gamry three electrode system where the reference electrode was Ag/AgCl, counter electrode was carbon and the working electrode was the metal sample. Fig. 5b shows a sectioned sample cut from an explanted prosthetic stem illustrating evidence of in-vivo corrosion.

**Results**

Severe corrosion/fretting was observed in 100% of AC; 24% of LCW; and 9% of HCW alloys. In-vitro potentiodynamic polarization tests in Hanks solution revealed that the AC alloy had the highest Ecorr value relative to LCW and HCW; however, relatively similar icorr values were obtained. With a variation of one order of magnitude in exchange current density (fig. 6a), a change of potential in the transpassive domain is evaluated. This is of great importance for an alloy, as it provides an estimation as to how the width of the passivation domain varies as shown in fig. 6b. The size of the passivation domain ranged in the following order: LCW > HCW > AC but the visual display of corroded surfaces ranged in the following order: HCW < LCW < AC. LCW possessed a homogeneous microstructure with a chromium rich passive oxide film, whereas HCW was inhomogeneous due to chromium carbide formation resulting in chromium depleted zones, thereby making it relatively more prone to pitting corrosion.
Conclusions

Different processing techniques resulted in microstructures that influence the electrochemical behavior of CoCrMo alloys. LCW alloys were the least prone to corrosion due to a more homogeneous microstructure and a uniform passive oxide film, whereas HCW alloy was inhomogeneous due to chromium carbide formation and thus, marginally more prone to corrosion as evidenced by the widths of the both passive domains.

Although the AC alloy had the highest corrosion potential (a thermodynamic property), 100% of the samples displayed evidence of corrosion. This is corroborated by the fact that AC also displayed the smallest passivating width. Although CoCrMo has been readily available as an orthopedic alloy since the 1930s, its future usage for prosthetic applications is controversial. One limitation of studying explanted prostheses is that the implant materials were manufactured more than a decade ago which imposes difficulties when comparing them to new generation materials. Recently, there has been a shift towards the usage of ceramic materials for femoral head components.

Acknowledgments

The authors would like to thank Dr. Carlos Lavernia for providing explanted hip prostheses.
References


