NEW HORIZON WORKSHOP 10

Bio-Tribocorrosion: Fundamentals and Advances in Orthopaedics

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Bio-Tribocorrosion Fundamentals to Orthopaedic Surgeon and Researcher

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TKA and THA are now common surgical interventions allowing a raising number of patients to recover mobility. The increasing success rate of these surgeries is related to the continuous improvements in clinical practices, in biomechanics and in materials development and shaping. Moreover, for joint implants tribological optimisation – essentially reduction of wear and friction - was achieved by coupling of appropriate materials such as UHMWPE, CoCrMo alloys and ceramics and by tailoring surface finish and contact geometries to reduce contact pressure and reinforce hydrodynamic lubrication. Thanks to these effort and the introduction of metal-on-metal or ceramic on ceramic hip joint prostheses the severe problem of UHMWPE wear and associated particles disease, which is one the major implant lifetime limiting factors, could be significantly attenuated. However, concerns have arisen about the long-term stability of metal on metal implants linked to the release into the body of metallic nano sized particles and ions that may trigger adverse body reactions. Further, the failure of a large number of large head THA due to severe degradation of the stem/trunnion/ball interface is jeopardizing the use of these otherwise successful metal on metal implants.

Degradation of bearings implant materials results has been mainly discussed in terms of mechanical strength versus loading and lubrication conditions. Little attention was paid to corrosion processes (dissolution of metal into the body liquid, build up of surface oxide films, adsorption of molecules on the metal surface) and their influence on the overall implant degradation. The reason for that is the inherent complexity of wear-corrosion interactions (tribocorrosion) and the lack of robust experimental and theoretical investigation tools. Recently, significant progress in understanding of tribocorrosion of passive metals (i.e. metals, such as titanium, stainless steel and CoCrMo alloys, that form spontaneously a thin oxide layer when immersed in aqueous solutions) has been made and mechanistic models were developed and verified on laboratory scale systems [1,2].

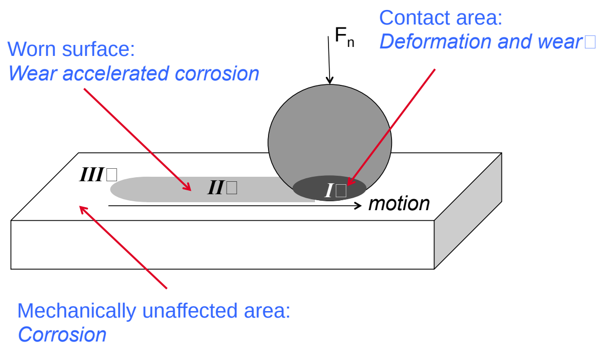

***Figure 1**: Model tribocorrosion system: Three zones (I, II, III) experiencing different degradation phenomena can be identified.*

A model tribocorrosion situation is shown in **Figure 1** that illustrates a mechanically and chemically inert ball sliding against a passive metal plate. The whole contact is immersed in an aqueous solution. Three zones (I, II and III) can be identified [2].

Zone I (the actual contact zone) is subject to mechanical loading (compression, friction) and is thus subject to a number of phenomena: frictional heating, elastic and plastic deformation, breakdown of the passive film, ejection of metal wear particles. Chemical reactions can profoundly affect the mechanical response in zone I as shown in **Figure 2**.

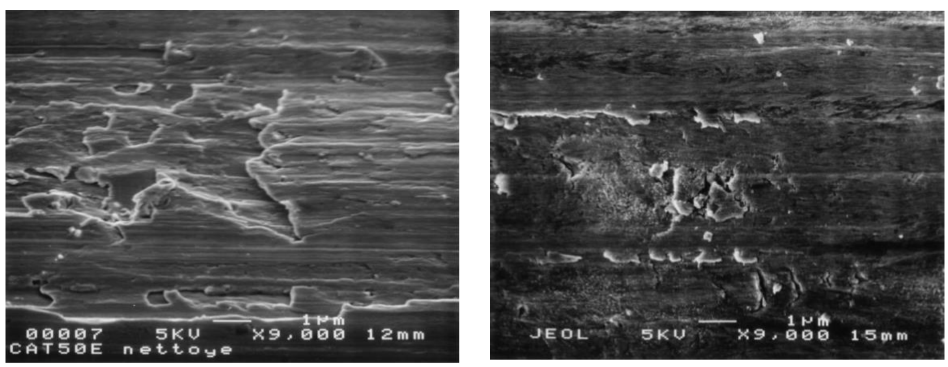

***Figure 2**: Worn surfaces of 316L stainless steel after rubbing against an alumina ball in acid environments. Left: in absence of passive film the surface presents large plastic flow but no signs of breakdown. Right: under passive conditions (presence of a passive film on the surface) cracks develops and wear particles form [3].*

The worn surface (Zone II) has undergone some depassivation (removal of the passive film and exposure of bare metal to the solution) resulting either from cracking of friable passive films, plastic deformation of the metal or from the detachment of metallic wear particles. Thus Zone II is subject to enhanced corrosion (wear accelerated corrosion) that can exceed by order of magnitudes the typical corrosion rates observed on passive metals. The wear accelerated corrosion rate can best be investigated using potentiostatic electrochemical techniques combined with tribological tests. Figure 3 schematically illustrates such a configuration. The potentiostat is an electronic device that imposes a selected electrode E potential between the working electrode WE (the metal under investigation) and a stable reference electrode by passing an appropriate current I between the working electrode and an auxiliary counter electrode CE. The potential E is the driving force for corrosion reactions and can be adjusted to the specific potential spontaneously attained by a metal in a given situation (for example implant in body fluid). In absence of side reactions, the current I corresponds to the corrosion rate of the metal. So, the technique illustrated in **Figure 3** allows one to simulate different corrosion conditions by simply selecting the appropriate potential E and to measure the corrosion rate by monitoring the corresponding current I. As an example, the graph in **Figure 3** shows that the onset of rubbing leads to a sudden enhancement of the current as a result of wear accelerated corrosion of the investigated CoCrMo alloy. As depassivation ceases the current recovers a low value characteristic of the passive state.

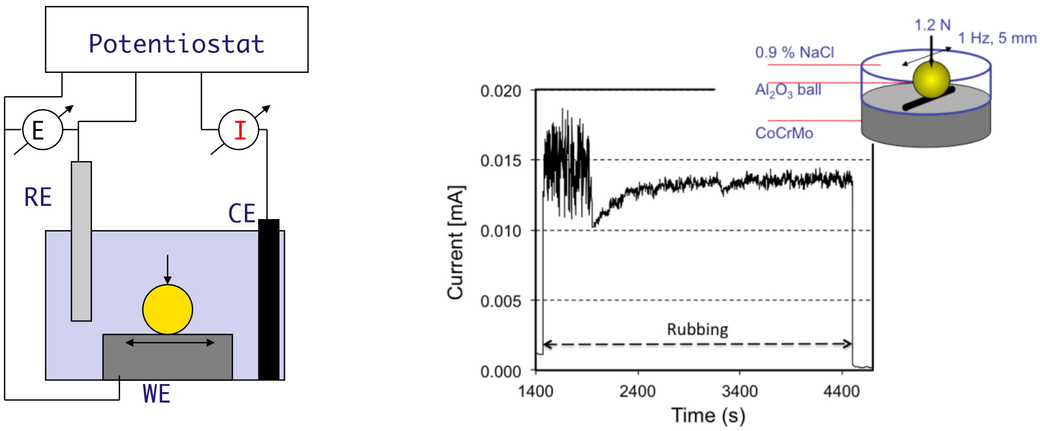

Figure 3 *Left: schematic potentiostatic three electrode set-up combined with a tribological experiment. An inert ball (yellow) is loaded against the metal WE and moves against it. The whole contact is immersed in an aqueous solution. Right: example of current response of a CoCrMo alloy rubbing against an alumina ball in sodium chloride solution under applied passive potential [4,5].*

Zone III in Figure 1 corresponds to the mechanically unaffected metal surface. This area is concerned by corrosion only. Despite the absence of direct interaction with the ball, the rubbing nevertheless affects the corrosion in Zone III. Indeed, under typical tribocorrosion conditions a galvanic coupling establish between zone III (passive, "noble" metal) and zone II (depassivated "non noble" metal). As a consequence, the electrode potential of zone III tends to shift toward lower potentials with a consequent change in corrosion rate. Depending on the specific situation, the corrosion rate of III can differ substantially from the situation in absence of rubbing. For example, negative shifts in potential in the order of 200-300 mV were observed on CoCrMo alloys tested in hip joint simulators equipped with electrochemical set-ups. From corrosion measurements, it is known that such a shift may increase the corrosion arte of CoCrMo alloys up to one order of magnitude. Considering the large mechanically unaffected areas of hip joints it is to wonder to which extent

In this paper we will briefly introduce the main tribocorrosion models and present a preliminary attempt to apply them to the situation of metal-on-metal hip joints with the aim is to assess the impact of tribocorrosion for understanding and controlling implant degradation.

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Clinical Aspects of Bio-Tribocorrosion in Orthopedics

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There are well-known benefits of head and neck modularity in total hip arthroplasty including intraoperative flexibility, the ability to change a head at a later date, if indicated, and decreasing implant inventory. While there were early concerns after the introduction of this modular head-neck junction in the late 1980s and early 1990s due to mechanically assisted crevice corrosion (MACC),[1,2] design and manufacturing improvements led to near universal adoption in contemporary arthroplasty. More recently, additional forms of femoral component modularity have been introduced including modular necks that allow the surgeon to independently control femoral fixation and hip center restoration. These modular necks allow adjustment of leg length, offset and version in an independent fashion. However, there are recent reports of adverse local tissue reactions (ALTR) associated with MACC at modular metal/metal junctions that are of concern to the adult reconstructive orthopaedic surgical community.

MACC-associated ALTRs

Head/Neck Modularity

The reported cases of MACC-associated ALTRs in primary metal-on-polyethylene total hip replacements are from multiple manufacturers with several different designs.[3] The geometry of the taper varied as did the metal composition of the head/neck junction (Ti-alloy/Co-alloy and Co-alloy/Co-alloy). The head sizes are varied from 28 to 40 mm – this is not simply a problem related to large femoral heads.

Cross-sectional imaging typically demonstrated a large fluid collection around the hip similar to what has been reported as and called "pseudotumors" in association with failed metal on metal bearings.[4,5] Serum metal levels demonstrated a fairly consistent finding in that serum cobalt levels were differentially elevated over serum chromium levels with respect to well-functioning metal-on-polyethylene devices.[3,6]

Typical intaoperative findings included black deposits at the head-neck junction associated with effusions, discoloration of the pseudocapsule and in some cases, granulomatous masses. Histological examination revealed regions of intense perivascular lymphocytic infiltration, as appearance similar to so-called ALVAL (aseptic lymphocyte-dominated vasculitis associated lesion) in metal on metal bearings.[7] In many tissue sections there were large areas of necrosis.

At revision surgery, well-fixed femoral components were retained, corrosion products were gently removed from the neck and a ceramic head with a titanium sleeve was inserted. Postoperatively, serum cobalt levels were observed to decrease, approaching the values in patients with well-functioning metal-on-polyethylene primary total hip replacements with modular heads.

Neck/Body Modularity

MACC-associated ALTRs have also been observed in patients with corrosion at the neck body junction in a modular neck prosthesis.[8] The bearing surfaces were either metal-on-polyethylene or ceramic on polyethylene. The patients reported to date have had a single stem design which has been subsequently recalled by the manufacturer. This implant had a beta-titanium alloy stem (TMZF) with a cobalt-alloy neck. The presenting symptom was primarily pain.

As in the cases with ALTR due to MACC at the head/neck junction described above, the diagnostic work-up typically revealed a large fluid collection on MARS-MRI although this was not a universal finding. Likewise, serum cobalt levels were differentially elevated over serum chromium levels and the serum titanium levels were similar to reference values.

Retrieved devices revealed evidence of MACC at the neck/body junction of varying severity. Histopathological examination revealed areas of necrosis and intense perivascular lymphocytic infiltration similar to the appearance of the ALTRs described above in association with MACC at head-neck junctions.

Discussion

Whether it is observed in patients with metal-on-metal bearings or patients with non-metal-on-metal bearings with MACC at modular junctions ALTRs seem to be related to the quantity of metal debris released from wear, corrosion or a combination of the two (tribocorrosion). While a threshold level of metal in the synovial fluid, periprosthetic tissue or bloodstream has not been defined, there is a clear association between ALTRs and high levels of metal in the bloodstream (whole blood or serum).[9-11]

The total exposure to metal debris is governed by additive and synergistic effects. The additive effect relates to a simple summation of metal debris from any metal surface, including a bearing surface or a surface interfacing with bone, cement or a metal modular component. The synergistic effects can be more subtle. Examples of synergistic effects include 1) third body wear of a metal bearing surface by virtue of the presence of particulate corrosion products from MACC at modular junctions, 2) bearing surface corrosion due to transient depassivation during the wear cycle, and 3) cathodic polarization effects whereby a tribocorrosion process at one location on a femoral stem (eg. a bearing surface) can decrease the tribocorrosion resistance at another location (eg. a modular metal/metal interface).

To demonstrate the importance of these additive and synergistic effects, it has recently been reported that MACC at modular junctions has been observed in failures related to ALTRs in association with large head metal-on-metal total hip replacements.[12] In some cases it has been estimated that the amount of debris released from the modular junctions exceeds that released from the bearing surfaces.[12] Interestingly, ALTRs have only been reported in association with modular conjunctions involving at least one cobalt alloy component. There are a variety of factors that may contribute to MACC at modular junctions. These include head size, taper geometry, material composition, metallurgical processing, surface finish, neck offset and length, contamination of the taper interface during assembly, and design-related factors. Several of these factors are under control of the manufacturer whereas some are under control of the surgeon.

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