In-vivo degradation mechanism of Ti-6Al-4V hip joints

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ABSTRACT

In-vivo exposed Ti-6Al-4V implants were investigated to determine the degradation mechanism occurring during the articulating movements of the hip joint in the human body. Failed implants were compared to Ti-6Al-4V samples, which were tested in the laboratory for their tribocorrosion performance. The results strongly indicate that degradation of Ti-6Al-4V has occurred with the same mechanism for both the implants and the laboratory tested samples and, hence, block-on-ring tribocorrosion testing was found to be a useful tool for mimicking the degradation occurring in the body. The degradation mechanism was concluded to be of combined mechanical and chemical nature. Wear debris is formed and accumulated in large flakes (100 μm). Upon further sliding the flakes are pressed into the surface and ultimately crushed into small, brittle particulate debris (<5 μm), which is released from the surface. It is suggested, that the small brittle particulate debris has a more detrimental effect in the hip joint than the large flakes due to a stronger reaction of the peri-prosthetic tissue. Also, Al-oxide particles are formed as part of the degradation mechanism.

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1. Introduction

Materials used in artificial hip joints have to meet high demands. The optimal material should be biocompatible, corrosion resistant, sufficiently strong to sustain the cyclic loading endured by the joint, have low modulus of elasticity to minimize bone resorption, and high wear resistance to minimize debris generation. Ti-6Al-4V is widely applied as hip implant material, because it combines most of the abovementioned properties [1,2]. A common assembly of an artificial hip joint consists of a Co-Cr-Mo femoral head articulating in a Ti-6Al-4V acetabular cup with a polymer liner (e.g. ultra high molecular weight polyethylene, UHMWPE) separating the two metallic parts. Although to date all commercial hip joints have to meet high demands. The degradation of Ti-6Al-4V subjected to tribocorrosion conditions has previously been studied [7,8,12–16]. However, most often laboratory samples instead of real implants were investigated and, consequently, the degradation mechanism is still not completely understood. The tribocorrosion performance of Ti-6Al-4V is generally characterised by four main factors: Electron configuration, oxide formation, crystal structure and the presence of hydrogen. Each of these is addressed below.

1.1. Electron configuration

Titanium has a very low d-bond character and is therefore very active and will easily react with other metals [8]. This could result in adhesive wear mechanisms of Ti-6Al-4V on sliding against other metallic surfaces. Furthermore, Ti-6Al-4V will easily react with oxygen as well as hydrogen, as described in the following.

1.2. Oxide formation

Titanium is easily oxidised and if Ti-6Al-4V is subjected to air at low temperatures an oxide layer with a thickness up to 10 nm will spontaneously form [1,13]. The native oxide layer protects the surface, but is easily removed mechanically and then the surface will be...
exposed to the surrounding environment. The oxide layer will form again, but the loosened oxide particles may act as three-body abrasive particles leading to increased wear degradation of Ti-6Al-4V [12]. When Ti-6Al-4V is sliding against softer materials, like UHMWPE, the oxide particles will also have a detrimental effect, because they will become embedded in UHMWPE and continued degradation occurs during subsequent sliding [13].

1.3. Crystal structure

The crystal structure of titanium plays a significant role in the tribological degradation of Ti-6Al-4V. The α-Ti phase has a hexagonal crystal structure, which involves few slip systems for plastic deformation. Since the axial ratio in α-Ti, c/a, is smaller than for densest packing, the prismatic planes become more favourable for slip rather than the basal plane of the hexagonal unit cell. Such prismatic slip causes an increased degree of plastic deformation [17]. Therefore, the α-phase of Ti-6Al-4V is more susceptible to plastic deformation compared to other h.c.p. materials. Plastic deformation and hardening of the near-surface region is a common theme in several postulated models of tribological degradation of Ti-6Al-4V [18,19]. The β-phase has a b.c.c. crystal structure and, accordingly, is responsible for high strength of the Ti-6Al-4V alloy. The amount and distribution of the two phases in the microstructure will control the mechanical behaviour of the alloy.

1.4. Hydrogen

Titanium has a large affinity for hydrogen. Hydrogen causes embrittlement of Ti-6Al-4V due to both the formation of hydrides and the presence of hydrogen in solid solution. As a result, hydrogen contributes to the overall release of debris [13,20–23]. The solubility of hydrogen is significantly different for the α- and β-phases in Ti-6Al-4V. The α-phase can maximally contain about 10 at% hydrogen without the formation of hydrides, while the β-phase can contain up to 50 at% hydrogen without hydride formation [22]. Furthermore, the rate of hydrogen diffusion is several orders of magnitude higher in the β-phase than in the α-phase [24]. As a result, hydrogen will preferentially be transported within the β-phase and form hydrides within the α-phase along the α/β boundaries. Therefore, the distribution of the two phases in the microstructure of Ti-6Al-4V strongly affects the influence of hydrogen dissolution [23]. It is also important to note that hydride precipitation can occur in materials with non-dangerous average concentration levels of hydrogen; this is observed at slip bands and crack tips [25].

The present study aims to improve understanding of the degradation mechanism of Ti-6Al-4 in the artificial hip joint. In the literature, the tribocorrosion performance of Ti-6Al-4V is generally investigated on a laboratory level, applying standard tests for well-defined sample geometries [12,14–16,26–29]. In contrast to these well-controlled laboratory conditions, which only simulate the conditions in the human body, the present work reports on the failure of actual implants, which were used in-vivo and were retrieved from the human body after several years of active service. Microstructure investigations of these real implants were supplemented by laboratory tests on the same materials and the failure mechanism of Ti-6Al-4V hip implants is proposed on the basis of both investigations. To the knowledge of the authors, a comprehensive microstructure investigation of retrieved acetabular cups and the correlation to laboratory tests has not been reported previously.

2. Experimental methods

2.1. Implants as-retrieved from the human body

Two acetabular cups with appurtenant polymer liners were provided by a Danish Hospital. The implants have been part of an artificial hip joint in the human body and were retrieved, because the patients suffered from pain. According to the common procedure for hip replacements, only the acetabular cup and polymer liner were retrieved; the corresponding femoral heads remained in the human body. Consequently, the corresponding femoral head and femoral stem were not available for the present study.

Neither the age nor on the physical activities of the patients were accessible. Furthermore, it is not known how long the implants had been in service, but a long-time application of several years is anticipated, because of the severe failure marks observed on the acetabular cups and polymer liners. There is no documentation on applied materials and the manufacturing of the implants; this is usually not recorded for medical routine operations.

After retrieval from the human body, the implants were cleaned with water and soap followed by autoclaving. This procedure was performed at the hospital and was not further specified.

The design of the two retrieved implants of the present study is different, but the observed failure has a similar appearance and, therefore, no distinction between the two acetabular cups is made in the sequel.

One of the two investigated acetabular cups is shown in Fig. 1. The black coloured stains on the polymer liner (Fig. 1A) indicate the presence of metallic particles released from the acetabular cup. In addition, mechanical failure of the polymer liner was observed. The polymer liners were thinner in some regions and allowed direct contact between the metallic parts, where the polymer has been worn through completely (not visible from Fig. 1). As a result of the metal-to-metal contact, failure occurred in the inner-side of the Ti-6Al-4V acetabular

![Fig. 1. One of the two investigated acetabular cups.](image-url)
cups due to direct contact with the femoral head (Fig. 1B and C), which is a common failure occurring in hip replacements [7]. Other types of interaction may cause degradation of titanium parts such as cement-Ti wear interactions, and contact between the edge of the acetabular cup and the neck of the stem in outer positions of the hip. Therefore, this study should serve as a representative for all kinds of tribocorrosion of Ti-6Al-4V occurring in hip implants.

In addition to the above described failure of the polymer liner, which has occurred during service, some large cracks were also observed on the polymer liner, and these originate from the surgery tools. Furthermore, some metallic particles are found on the failure surface of the acetabular cups, which originate from the surgery tool used during retrieval of the implants. It should be emphasized that, in the present study, in-vivo failure of the implants occurred during service was carefully distinguished from surgery induced failure marks - the latter are not addressed in the present work.

2.2. Microstructure characterisation

Metallographic preparation for microstructure investigations was carried out for both cross section and top view samples. In some cases, a thin Ni-layer was electrodeposited onto the samples prior to embedding to ensure that the surfaces were not affected too much during metallographic preparation. Both Keller's and Kroll's etchant were used for microstructural etching and the results obtained with the two etchants were found to be similar.

Scanning electron microscopy (SEM) was performed with a JEOL JSM-5900 with LaB6 filament applying secondary electron imaging (SEI) and backscattered electron imaging (BEI) as well as energy dispersive spectroscopy (EDS, Oxford Instruments) for quantitative chemical analysis. Occasionally, samples were coated with carbon to avoid charging during SEM investigations.

X-Ray diffraction (XRD) for qualitative phase analysis was carried out with a Bruker AXS D8 Discover diffractometer equipped with Cu-Kα radiation. XRD on the curved acetabular cups required particular care for correct mounting of the sample and aligning the X-ray focus on the sample surface.

Microhardness measurements were performed in Vickers geometry applying a Future-Tech FM 700 microhardness tester with a load of 10 g.

2.3. Laboratory testing of tribocorrosion performance

The tribocorrosion performance of the Ti-6Al-4V-alloy was tested under laboratory conditions at room temperature in a block-on-ring setup [30]. Experiments were carried out in accordance with the ASTM Standard G77-98. An illustration of the test setup is shown in Fig. 2.

Ti-6Al-4V was used as block and alumina (99.9% Al2O3) as ring. The contact areas on Ti-6Al-4V and alumina were polished with SiC paper of grade 500 before the tribocorrosion experiments. A load of 2 kg was applied to establish contact between the block and the ring. Electrochemical measurements were performed in the block-on-ring setup with a standard three-electrode setup. As the electrolyte should resemble the natural body fluids in the hip joint, a commercially available Ringers solution (Oxoid A/S, Denmark) with composition 2.25 g/l NaCl, 0.105 g/l KCl, 0.12 g/l CaCl2·6H2O and 0.05 g/l NaHCO3 and pH = 7 was used.

Under the tribocorrosion experiments the sample was kept at a fixed potential, and two different potentials were used: -200 and -2000 mV vs. SCE. A potentiostat Gill AC ACM Instrument with Voltalab 4 software was used. The experiments were performed without sliding during the first 10 minutes, followed by 120 minutes sliding and completed with 10 minutes without sliding, which represents an appropriate test duration to obtain notable degradation of Ti-6Al-4V [31–33].

3. Results

3.1. Morphology of the failure area on the implant

The surface of the inner-side of the acetabular cup is shown in Fig. 3. Both the region, which has been attacked mechanically by sliding against the femoral head and the original unaffected surface are visible. The unaffected surface contains many voids and appears rough compared to the failure surface. The failure surface is smoothened and grinding grooves were observed, which originate from sliding against the femoral head during the articulating

![Fig. 3. Inner surface of the acetabular cup. The border between the failure surface and the unaffected surface is shown, A) SEI micrograph, B) BEI micrograph.](image-url)
movements of the hip joint. The BEI micrograph (Fig. 3B) reveals two different contrasts on the failure surface: a patch of bright and dark regions is observed. EDS measurements revealed no composition difference between the bright and dark regions. Furthermore, the thus determined composition at the surface was identical to the bulk composition. Since no oxygen was detected for the surface measurements, it is assumed that only a naturally grown oxide layer was present on the implant surface.

The failure surface is shown in Fig. 4. EDS analysis of a few particles on the failure surface revealed the presence of Co, Cr, and Mo, which suggests that the femoral head most likely consisted of a Co-Cr-Mo alloy. The Co-Cr-Mo particle marked by a circle in Fig. 4 measures about 1 μm x 3 μm. These dimensions would correspond to the width of the grinding grooves, which range from 0.5 μm to 3 μm. Cracks were observed on the failure surface (see arrows in Fig. 4) and are dominantly located in regions with a darker contrast, suggesting that the dark regions are more brittle than the bright ones. Furthermore, round particles with a black contrast were observed on the failure surface in Fig. 4. As for the cracks these particles are mainly located in the dark regions. Complementary BEI and SEI micrographs of such particles are shown in Fig. 5. The SEI micrograph suggests that the particles are positioned in the surface. The large contrast difference between the particles and the surrounding surface (BEI micrograph) indicates a significant composition difference, as is confirmed by EDS measurements of the particles, see Table 1.

The EDS analysis revealed that the particles contain an enhanced content of Al compared to the alloy composition. In addition, qualitative indications of enhanced O content (not quantified) indicate that the particles consist most likely of Al-oxide.

3.2. Microstructure investigation and phase analysis of failure surfaces on the implant

The microstructure of Ti-6Al-4V close to the failure surface is shown in Fig. 6. The two-phase microstructure is clearly visible, where large gray grains are α-Ti and the bright grains are β-Ti (black arrows). The microstructure underneath the failure surface is clearly heavily deformed by the femoral head during the articulating movements in the hip joint. The white arrow in Fig. 6A marks particles comparable to those observed on the failure surface in Fig. 5 and also EDS confirmed a similar chemical composition (cf. Table 1), i.e. enhanced contents of Al (and O) compared to the original alloy. The two white arrows in Fig. 6B indicate detachment of small flakes from the failure surface. EDS measurements revealed that these flakes consist of α-Ti. Obviously, the detachment has occurred in the vicinity of β-Ti. Deformation twins were observed close to the failure surface in the h.c.p. α-Ti grains, which are more susceptible to twin formation than b.c.c. β-Ti.

XRD measurements were performed on the failure surface and on polished cross sections for the unaffected sample region. Both XRD analyses revealed the presence of α-Ti and β-Ti (JCPDS no. 44-1294 and 44-1288, respectively). Although dedicated near-surface XRD measurements were carried out in grazing incidence geometry applying various small incidence angles to reduce the depth of analysis, no additional phases could be detected. Considerable peak broadening in the diffractogram from the failure surface complicates the identification of peaks with minor intensity. Peak broadening is consistent with heavy deformation as a result of sliding against the femoral head.

3.3. Tribocorrosion performance

After the block-on-ring tribocorrosion testing a wear track from the alumina ring was visible on the surface of Ti-6Al-4V. It was observed that the electrolyte was discoloured after testing, indicating that a large amount of released particulate debris from Ti-6Al-4V was dispersed in the solution. The size of the particulate debris in the electrolyte was estimated with SEM to be less than 5 μm.

After the two different applied potentials, -200 and -2000 mV vs. SCE, no difference in the degradation mechanism was observed. The following descriptions are based on the sample tested at -2000 mV vs. SCE.

The wear track on Ti-6Al-4V after tribocorrosion testing is shown in Fig. 7. Large flakes (> 100 μm, marked in Fig. 7B) were observed in
the bottom of the wear track, but the size of the flakes does not correspond to the particulate debris (<5 μm) found in the electrolyte. There is a clear difference between the failure surface and the unaffected surface, especially visible in the BEI micrograph (Fig. 7A): Regions with dark and bright contrast were observed (BEI) on the failure surface, but not on the unaffected surface. The dual-contrast appearance of the surface is magnified in Fig. 8, both in top-view (Fig. 8A) and from polished cross sections (Fig. 8B-C). The sample in Fig. 8C is prepared without mounting in resin, which reduced charging during examination. For this sample, the cross section analysis revealed the depth of the dark region (Fig. 8C). On both polished cross sections (Fig. 8B-C) it is observed that particulate debris with a size smaller than 5 μm is released from the surface. The small size of this particulate debris is comparable to the size of the particles found in the electrolyte after the experiment, as described above. Cracks and small round particles with a black contrast were also observed in the dark regions on the top-view image (Fig. 8A). The small round particles (arrows in Fig. 8A-C) were analysed with EDS; the average composition of measured from several particles is given in Table 2.

Enhanced contents of Al (and, qualitatively, O) as compared to the alloy composition might indicate that the particles consist of Al-oxide, as for the failed implant (cf. Table 1).

To clarify the origin of the dual-contrast surface, the alignment of the dark regions in relation to the underlying microstructure was thoroughly investigated with SEM, but no indication that its location is related to the microstructure underneath was found. Also, EDS spot analyses was carried out, but no significant difference between the two regions was found, despite the obvious contrast difference in the BEI micrographs (Figs. 7A and 8A). Not even oxygen was found, which can exclude that dark areas result from oxidation. EDS mapping covering both dark and bright regions (Fig. 9) indicated lower Ti contents in the dark regions than in the bright ones. Similar indications are observed for V, albeit less clear. Since no indications of enhanced X-ray intensity of any element in the dark regions were found, the X-ray intensity difference between light and dark regions must be a consequence of specific density differences between these regions, which would be consistent with the observed contrast differences in the BEI micrographs. The specific density difference is probably caused by porosity and micro cracks as well as the large visible cracks perpendicular to the sliding direction.

The microhardness in the dark regions was found to be significantly higher than in the bright regions. The bright regions have an average hardness value of 470 HV0.01, whereas dark regions have a value of 610 HV0.01.

A large flake was observed on the failure surface of the tribocorrosion tested sample, see Fig. 10. The size of the flake (>100 μm) is comparable with the flakes observed in the bottom of the wear track in Fig. 7B. The flake is most likely an accumulation of wear debris loosened from the surface when sliding against the alumina ring and, if the flake is pressed into the surface again, it is anticipated that it would appear similar to Fig. 8B and C. Cracks located in the flake and in the dark contrast base material below the flake indicate the brittle character of these regions.

The dark contrast region was investigated with TEM combined with EDS and electron diffraction and Al2O3 (corundum) particles could be identified. These particles correspond to the dark particles in Figs. 8A and 9, where enhanced Al contents were detected (Tables 1 and 2). Due to the risk of ion-milling induced artefacts in titanium [34–36], microstructure analysis was not carried out on the TEM prepared sample.

XRD was performed on the tribocorrosion tested samples (Fig. 11). For the failure surface (a), peaks are severely broadened consistent with a highly deformed surface as compared to the unaffected surface (b). The same phases were identified from both measurements, although identification of β-Ti on the failure surface was complicated due to peak broadening. XRD was also performed with varying grazing incidence angles to obtain information over various depth ranges underneath the surface, but these investigations did not reveal other phases.

4. Discussion

The failures observed on the in-vivo exposed Ti-6Al-4V implants and the tribocorrosion tested Ti-6Al-4V samples have many similarities:

i) Black marks observed on the polymer liners of both retrieved implants indicate that metallic particles were released from the implant and pressed into the polymer (cf. Fig. 1). After the tribocorrosion experiments in the present work the electrolyte was discoloured due to the presence of particulate debris from the degradation of Ti-6Al-4V.

ii) The same phases were identified by XRD for the failure surfaces of both the in-vivo exposed implants and tribocorrosion tested samples.

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**Table 1**

Chemical composition (wt%) of particles in Fig. 5. The presented values are an average over several measurements.

<table>
<thead>
<tr>
<th></th>
<th>Ti</th>
<th>Al</th>
<th>V</th>
</tr>
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<tbody>
<tr>
<td>wt%</td>
<td>78.3</td>
<td>18.1</td>
<td>2.6</td>
</tr>
</tbody>
</table>

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**Fig. 6.** BEI micrograph showing the microstructure in the failure area: α-Ti (gray) and β-Ti (bright). Particles near the surface in (A, white arrow) are similar to the particles shown in Fig. 5. Detachment from the failure surface is shown in (B). Note, the polished cross section shown in (B) was etched, whereas (A) was not etched, which explains the different appearance of both micrographs.
iii) A checker-board pattern of light and dark contrast was observed on the failure surfaces of both the implants and the laboratory tested samples (cf. for example Figs. 3B and 7A). For both types of samples, the light and dark regions cannot be related to different chemical composition (apart from the presence of Al₂O₃ particles, see below), but higher microhardness values and the occurrence of cracks were found in dark regions for both the implant and the tribocorrosion tested samples.

iv) In the brittle dark regions of the checker-board pattern of both the implant and the tribocorrosion tested sample Al-oxide particles were detected. Although it cannot be excluded that Al₂O₃ (at least part of it) found on the laboratory-tested sample originates from the applied counterpart of the tribocorrosion experiment, the in-vivo exposed implant has not been in contact with Al₂O₃, because the femoral head consisted of a Co-Cr-Mo alloy.

According to the present results, the following failure mechanism is proposed: When the femoral head moves within the acetabular cup after the polymer liner has been worn through, wear debris from the acetabular cup is formed. An accumulation of wear debris from the Ti-6Al-4V alloy yields larger flakes (>100 μm), which are pressed into the surface during continued sliding. This causes a dark contrast on the failure surface, as observed in the present study. Due to the brittle nature of these dark regions, cracks occur and fine particulate debris (<5 μm) is released from the failure surface upon further sliding in the hip joint. The fine particles are harmful, because the large surface/volume ratio of the small particulate debris yields higher reactivity [3,37] and they represent a larger biochemical risk to the body because they are smaller than 10 μm [38]. The particulate debris will ultimately be transported through the body, cause inflammation in the peri-prosthetic tissue and loosening of the implant. Furthermore, the particulate debris will act as three-body abrasive particles contributing to increased degradation of the sliding parts.

In the literature, the degradation of Ti-6Al-4V is often related to the presence of hydrogen and corresponding formation of hydrides [10,13,20–23]. Hydrogen is expected to diffuse through β-Ti and react with α-Ti along the α-β phase boundaries [24,39]. As a result, hydrogen embrittlement would mainly occur in α-Ti near α-β boundaries – exactly as observed in the present study (Fig. 6). However, neither enhanced concentrations of hydrogen nor the presence of crystalline hydrides were detected. Accordingly, no unequivocal evidence was obtained that hydrogen plays a role in the degradation mechanism. Nevertheless, the brittle regions with dark contrast (i.e. lower density) on the failure surface could be a consequence of the presence of hydrogen or hydrides. In this respect, also the presence of Al-oxide particles underneath these regions could be related to the formation of hydrides and vice versa.

Table 2
Chemical composition (wt%) of particles on the failure surface after tribocorrosion testing (cf. arrows in Fig. 8).

<table>
<thead>
<tr>
<th></th>
<th>Ti</th>
<th>Al</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>wt%</td>
<td>76.0</td>
<td>20.7</td>
<td>3.3</td>
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Thermodynamically, the reaction of water with Ti-Al-V would lead to the development of Al₂O₃, because the formation of this oxide has the most negative Gibbs energy per mole of oxygen [40]. Simultaneously, the released hydrogen atoms could diffuse into the titanium matrix and form hydrides.

Reported evidence for the presence of hydrides is often based on an intensity maximum in X-ray diffractograms at 39.5 °2θ, which is considered as γ-TiH (see for example [10,20,41]). In the present work, this intensity maximum was observed as well (Fig. 11), but attributed to (110) β-Ti instead, which would be consistent with the occurrence of (211) β-Ti at 71.6 °2θ. Furthermore, as Fig. 11 shows, this peak at 39.5-2θ is also pronouncedly present in the unused (but ground and polished material) Ti-6Al-4V diffractogram, which corroborates the interpretation that this peak should be attributed to β-Ti rather than γ-TiH.

5. Conclusion

The degradation of Ti-6Al-4V was investigated for in-vivo exposed hip implants as well as for laboratory samples tested for tribocorrosion. The similarity between the in-vivo failed implants and laboratory tested samples clearly points out that the degradation mechanism of Ti-6Al-4V in the articulating hip joint can be mimicked in a block-on-ring tribocorrosion test as applied in this study.

When the femoral head moves within the acetabular cup during movement of the hip joint and the polymer liner is (locally) worn away, direct contact is established between the femoral head and the Ti-6Al-4V acetabular cup. As a result, the Ti-6Al-4V surface is heavily deformed by the femoral head and wear debris from the Ti-6Al-4V surface is generated. The wear debris is accumulated into large flakes (>100 μm), which are pressed down into the surface during further sliding in the hip joint. These regions are brittle and contain many cracks, and they will be crushed into fine (<5 μm) particulate debris, which ultimately is released from the failure surface and may affect the peri-prosthetic tissue. In particular, fine particles are considered to pose a high biochemical risk rather than the large flakes.

Al-oxide particles are found in the dark regions on both in-vivo exposed implants and laboratory tested samples. It is anticipated that the particles are a part of the degradation mechanism in Ti-6Al-4V, for example through an interaction of water molecules with Al in solid solution, but further investigations are needed to verify this.

It cannot be excluded that hydrogen affects the degradation mechanism, but no unequivocal evidence for its presence was found in the present study.

Fig. 9. EDS mapping on distinctive regions of dark and bright contrast on the failure surface after the tribocorrosion experiment. SEI micrograph (A) and corresponding EDS maps of Al, Ti, V, and O (B).

Fig. 10. Large flake observed on the failure surface after the tribocorrosion experiment.

Fig. 11. XRD patterns of Ti-6Al-4V after the tribocorrosion test from the failure surface (a – black line) and from the unaffected surface (b – gray line).
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References

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