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Mechanisms of Premature Fracture in Modular Neck Stems Made of CoCrMo/Ti6Al4V and Ti6Al4V/Ti6Al4V Alloy

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Abstract: In this paper, we present the mechanisms of premature fracture of modular neck stems in two case studies: (I) when the neck and stem are both made of the same Ti6Al4V alloy, and (II) when the neck and stem are made from two different alloys, CoCrMo and Ti6Al4V alloy. Our study integrates two orthopedic patients who have undergone primary uncemented THA for usual indications in two orthopedic centers (Community Health Centre and University Medical Centre). Both centers are part of the national public health care system. Both surgeries were performed by two skilled orthopedic surgeons with more than 10 years of experience in THA. The survivorship of the modular neck of cast CoCrMo alloy was 24 months. The survivorship of the modular neck from Ti6Al4V alloy was 84 months. Multivariate analyses were performed to assess the differences in the fretting, corrosion, and fatigue of the two prematurely failed modular neck stems: stereo light microscopy (SLM), scanning electron microscopy (SEM), X-ray energy-dispersive spectroscopy (EDS), and electron backscatter diffraction (EBSD). Patient demographic information, including sex, age, body mass index, survivorship of implants, and reason for the revision, was collected from medical records. We found that fretting and fatigue occurred on both neck-stem retrievals due to additional galvanic corrosion, but the CoCrMo/Ti6Al4V alloy system suffered more corrosion due to additional galvanic corrosion and fractured earlier than the Ti6Al4V/Ti6Al4V metal alloy system. Both metallic alloy systems used in this application are known to be highly corrosion-resistant, but the bio-tribo-corrosion processes need to be understood in detail and characterized so that appropriate improvements in design and materials can be made.

Keywords: total hip arthroplasty; modular neck; Ti6Al4V alloy; CoCrMo alloy; corrosion

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1. Introduction

Modular neck stems were introduced to hip endoprosthesis with the expected benefits of reducing pain and improving the range of motion and leg length [1–3]. Besides classic stems (Figure 1a,c), Wright Medical Technology/Microport, Stryker, Depuy, Lima Corporate, Zimmer, Adler Ortho, Cremasoli, and others are recognized worldwide manufacturers of modular neck stems (Figure 1b). The stem and the neck are available in different sizes and different neck angles, as seen in Figure 1b, to tailor the implant to the individual patient. Increased implant modularity with modular necks made from Ti6Al4V and stems from the same alloy has generated interest in recent years because the various neck sizes, offsets, lengths, and design configurations allow the surgeon to optimize the range of motion and the patient's leg length. However, there have been concerns due to early in vivo fractures as well as adverse tissue reactions related to corrosion at the neck–stem interface [2–11].

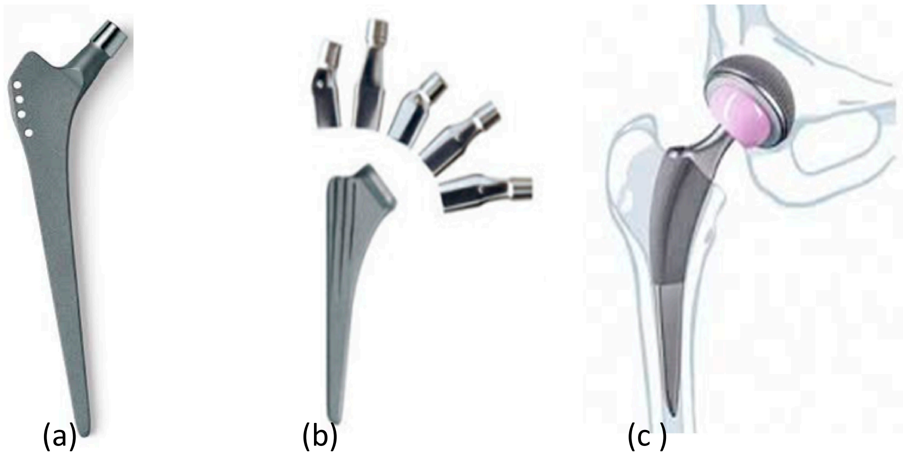

Figure 1. (**a**) Classic Ti6Al4V femoral cementless ZM stem; (**b**) modular stem with 5 different modular necks; the stem and the neck are in different sizes with different neck angles to tailor the implant to the individual; (**c**) total hip endoprostheses, classic stem with an acetabular composed of a ceramic head, highly cross-linked PE cup, and a trabecular metal cup.

The presence of the neck–stem interface using titanium alloys makes the neck junction vulnerable to fretting, corrosion, and fatigue fracture. Several authors reported an early fracture of long modular necks made of Ti6Al4V alloy [5–11].

Many of the femoral modular stems suffer from premature fractures after total hip arthroplasty (THA) of the titanium alloy neck. Due to the results of in vitro investigations which presented better wear and mechanical properties, as seen in Table 1, a cobalt–chromium–molybdenum neck was introduced [9–13].

CoCrMo neck fractures have also been reported after only a few months of implantation [12,14]. Some reports have shown cases of fractured necks that could not be detracted from the stem pocket, requiring the replacement of the otherwise well-fixed femoral stems [2,4,7,11].

Table 1. Physical and mechanical properties of CoCrMo cast alloy [15] and Ti6Al4V alloy [16].

Material	Density (kg/m^3)	Elastic Modulus (GPa)	Poisson's Ratio	Thermal Conductivity (W/mK)	Specific Heat (J/kgK)	Thermal Expansion Coefficient (10^{-6}/K)	Melting Point (K)
CoCrMo	8768	283	0.29	14.8	452	12	1663
Ti6Al4V	4430	109	0.34	6.8	611	9.0	1878

The main aim of our work was to investigate mechanisms of premature failure of two case studies due to the fracture of the long neck in two different metallic alloy systems: the same alloy (neck and stem are both made from the same Ti6Al4V alloy with a survivorship of 84 months) and different alloys (neck made from CoCrMo alloy with better mechanical properties and a stem body made from Ti6Al4V alloy, with a survivorship of only 24 months) [12–14].

The research was a joint effort of orthopedic surgery clinicians and material scientists.

2. Materials and Methods

2.1. Patient Characteristics

The present study examines the outcomes of two orthopedic patients who underwent primary uncemented total hip arthroplasty (THA) for typical indications at two reputable orthopedic centers: the Community Health Centre and the University Medical Centre. Both centers are part of the national public health care system.

2.2. Surgery Characteristics

Both surgeries were performed by two skilled orthopedic surgeons with more than 10 years of experience in THA, performing at least 200 THAs yearly. A standard anterolateral approach was used in both cases. Preoperative planning was performed using analog templates on standard calibrated 110 cm AP pelvic X-rays. Both surgeries were performed according to the patient's preoperative planning and anatomical features to restore hip anatomy, preventing hip instability and minimal postoperative leg length discrepancy. Patients received routine follow-ups at institutional outpatient clinics at 3 months, 6 months, and 1 year postoperatively, and thereafter upon request of the patient and/or their family physician. The X-rays of the patients with failed implants are shown in Figure 2.

Figure 2. (**left** panel) Standard calibrated 110 cm AP pelvic X-rays of a fractured CoCrMo/Ti6Al4V modular neck of a 51-year-old male, survivorship 24 months. (**right** panel) X-ray of a fractured Ti6Al4V/Ti6Al4V modular neck of a 42-year-old male, lifetime 84 months.

The fractured surfaces of the CoCrMo modular neck of the different-metal system CoCrMo/Ti6Al4V with a survivorship of 24 months and the Ti6Al4V modular neck of the same-metal system Ti6Al4V/Ti6Al4V with a survivorship of 84 months are shown in Figure 3.

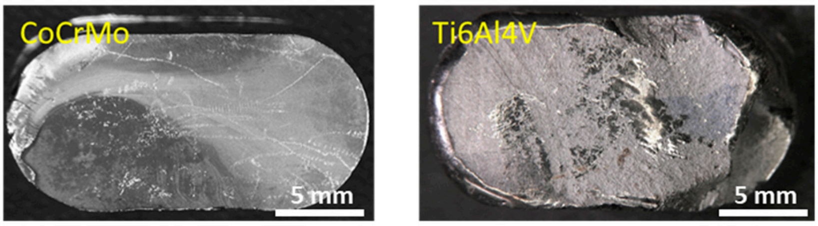

Figure 3. (**Left** panel) Fractured surface of CoCrMo modular neck of a 51-year-old male, survivorship 24 months. (**Right** panel) Fractured surface of Ti6Al4V modular neck of a 42-year-old male, survivorship 84 months. Stereo light microscope Tagarno FHD trend was used for the visualization of fractured surfaces of the CoCr Mo modular neck and Ti6Al4V modular neck.

2.3. Implant Characteristics

2.3.1. Modular Neck Stem Made of CoCrMo (Neck) and Ti6Al4V (Stem) Alloy

The fractured modular neck of cast CoCrMo alloy, manufactured by Wright Medical Technology/Microport, Profemur Plus Modular Neck size /°8 with reference PHAC 1254 (CoCr Mo alloy), was retrieved and provided by a community hospital. The femoral stem of forged Ti6Al4V alloy, manufactured by Wright Medical Technology Microport, was retrieved, with a stem size of 5 and length of 125 mm (Ti6Al4V alloy). The modular neck stem (CoCrMo/Ti6Al4V) is the femoral component of the hip endoprosthesis and Biolox Delta femoral head, size 32 mm PHA0410—the alumina matrix composite is a modern press-fit acetabulum acetabular component. The fractured sample was provided by the community hospital. The survivorship of the hip endoprosthesis was 24 months (2 years). The fracture surface of the retrieved implant is presented in Figure 3, left panel.

The chemical composition of CoCrMo cast alloy is presented in Table 2, and that of Ti6Al4V is presented in Table 3. The physical and mechanical properties of CoCrMo and Ti6Al4V are presented in Table 1.

Table 2. Chemical composition of CoCrMo (Mass%) cast alloy, ICP measurements at IMT.

Material	**Cr**	**Mo**	**Ni**	**Fe**	**C**	**Si**	**Mn**	**P**	**S**	**Ti**	**Co**
CoCrMo	29.5	6.6	0.25	0.07	0.35	0.7	0.5	0.2	0.1	0.1	balance

ICP—inductively coupled plasma spectroscopy, IMT—Institute of Metals and Technology, Ljubljana, Slovenia.

Table 3. Chemical composition of Ti6Al4V (Mass%), ICP measured at IMT.

Material	**Al**	**V**	**Fe**	**O**	**C**	**N**	**H**	**Ti**
Ti6Al4V	6.40	4.30	0.04	0.08	0.05	0.01	0.001	balance

ICP—inductively coupled plasma spectroscopy, IMT—Institute of Metals and Technology, Ljubljana, Slovenia.

The microstructure of CoCrMo alloys consists of face-centered cubic (fcc) and hexagonal close-packed (hcp) crystalline structures. Typically, the (fcc) phase is predominant at room temperature but the (fcc) $\rightarrow$ (hcp) transformation could be isothermally or strain-induced, as reported in detail in our previous paper [13].

The microstructure of Ti6Al4V alloy consists of a dual-phase microstructure, where the matrix is the Ti-α phase and the V-rich phase is the Ti-β phase, as reported in our previous paper [13].

2.3.2. Modular Neck Stem Made of the Same Ti6Al4V (Neck) and Ti6Al4V (Stem) Alloy

The fractured modular neck of forged Ti6Al4V alloy manufactured by Wright Medical Technology/Microport was retrieved, fractured, Profemur Plus Modular Neck size /°8 with reference PHAC 1254 (Ti6Al4V alloy). The femoral stem of forged Ti6Al4V alloy manufactured by Wright Medical Technology/Microport was retrieved, with a stem size of 8 and length of 140 mm (Ti6Al4V alloy). The modular neck stem (Ti6Al4V/Ti6Al4V) is the femoral component of the hip endoprosthesis and the Biolox Delta femoral head, size 32 mm PHA0410—the alumina matrix composite is a modern press-fit acetabulum component. The failed endoprosthesis was provided by the University Medical Center. The survivorship of hip endoprosthesis with a modular neck stem of the same alloy (Ti6Al4V neck and Ti6Al4V stem) was 84 months (7 years). The fracture surface of the retrieved implant is presented in Figure 3, right panel.

2.4. Sample Preparation

The retrieved Ti6Al4V stems and long modular necks of CoCrMo and Ti6Al4V alloys were cut using a Struers's saw for the preparation of metallographic samples and the samples for other investigations. For the microstructure analyses and surface chemistry measurements, the samples were ground with SiC 220 grinding paper (1 min), polished with MD Largo 9 m blue lubricant (5 min), and oxide-polished with MDCHEM OP-S (STRUERS GmbH, Zweigniederlassung, Austria) and H_2O_2 (10 min). The samples for the bulk microstructure analyses were additionally etched with Kroll's reagent.

2.5. Methods

2.5.1. Stereo Light Microscopy (SLM)

A stereo light microscope, Tagarno FHD trend, was used for the visualization of the fractured surfaces of the Ti6Al4V modular neck and the Co-Cr-Mo modular neck.

2.5.2. Scanning Electron Microscopy (SEM, SEM/EDS, SEM/EBSD) Analysis

The morphology and microstructure of the fracture surfaces were analyzed using a scanning electron microscope, JEOL JSM 6500-F (JEOL Ltd., Japan). The SEM images were acquired using an accelerating voltage of 15 kV, with a current of about 500 pA and a working distance of 10 mm. Secondary electron and backscattered electron images were acquired. The elemental compositions of the samples were analyzed using Oxford INCA EDS analysis. The EDS spectra were acquired using a 15 kV and 1 nA beam, with an acquisition time of 60 s for each spectrum. The EDS spectra were analyzed using INCA Energy software to determine the elemental composition and distribution in the sample. Electron backscatter diffraction (EBSD) was also used to determine the type of carbides present in the microstructure. A Nordlys EBSD detector (HKL) and a Channel 5 data analysis suite were used. The EBSD patterns were acquired at 15 kV accelerating voltage and 2 nA current.

3. Results

3.1. Modular Neck Stem Made of CoCrMo (Neck) and /Ti6Al4V (Stem) Alloys

The patient with the implanted hip endoprostheses with a modular neck stem manufactured from two different alloys (long modular neck of CoCrMo and stem of Ti6Al4V alloy) was an active 51-year-old male with a normal BMI; he maintained his physical condition by light cycling. He slipped on the stairs at home, suddenly had terrible pains, and panicked because he was motionless. X-rays confirmed a fractured stem neck and required urgent revision surgery (Figure 2, left panel). The survivorship of the modular neck stem was 24 months (2 years).

Figure 4 represents in the inner panel the SLM image of the fractured surface of the CoCrMo modular neck in the inner panel with the marked Zones A, B1, B2, C, and D.

Details of the first part of the fracture, marked as Zone A, are shown in Figure 4. Deposits of biological material were observed on the surface, as well as cracked carbide particles. The crack initiated on the surface of the CoCrMo modular neck stem (pink arrow in Figure 4) due to several different factors, but the dominant mechanisms were fretting and crevice corrosion. The CoCrMo femoral neck was dynamically loaded, exposed to a corrosive medium in the human liquids, and surrounded by a Ti6Al4V alloy with different electrochemical potentials. Constant micromotions caused repeated breakage of the passive oxide films and an unstable electrochemical environment within the crevice for both the cobalt alloy and Ti alloy passive films, as reported in the literature [17–20]. AES and XPS analyses of the thin oxide (passive film), described in detail in our previous studies [12,13], show that the oxide film on CoCrMo consists of Cr_2O_3 and traces of CoO_3 oxides with an estimated thickness of 2 nm. The oxide film on Ti6Al4V alloy consists of TiO_2 and traces of Al_2O_3 with an estimated thickness of 7 nm. Thermodynamic data of passive oxide formation as well as electrochemical studies on CoCrMo and Ti6Al4V alloy confirm that the re-passivation is much faster on Ti [21–26].

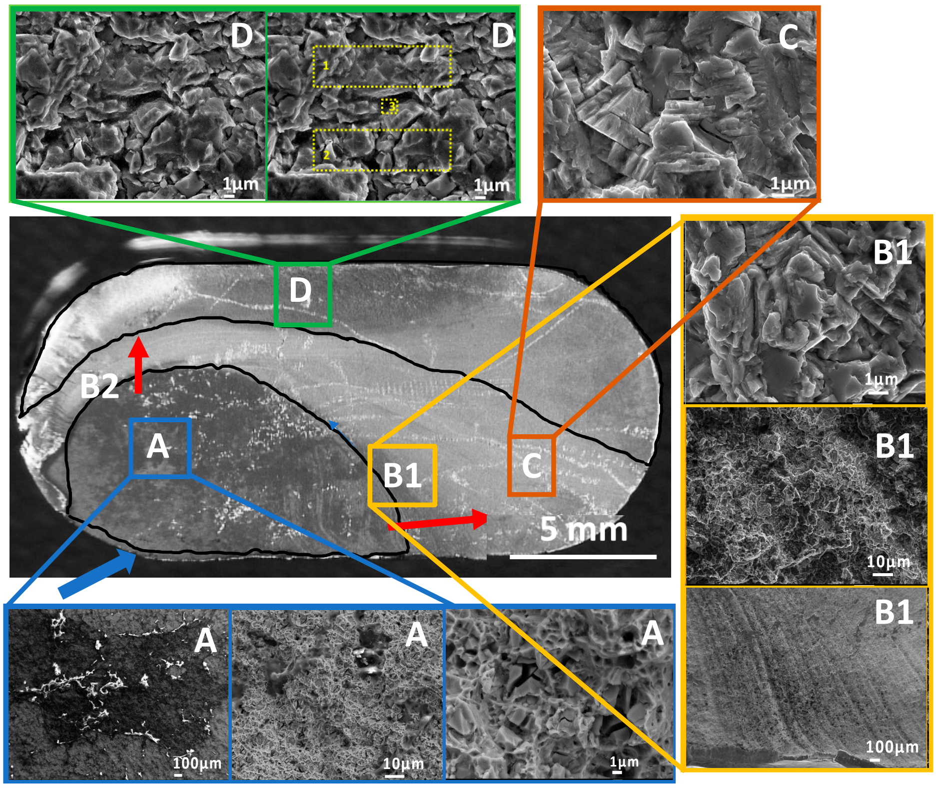

Figure 4. SLM of the fractured surface of CoCrMo neck on the main inside image represents the mechanism of CoCrMo alloy modular neck fracture. The blue arrow indicates the crack initiation; Zone A, the corroded fractured surface with deposited biological material, is shown in three SE images in three blue-marked panels: the **left** panel (**A**) at lower magnification, the detail of fatigue fracture and cracked carbides at higher magnification, panel (**A**) in the **middle**, and cracked carbide at highest magnification in the **right** panel (**A**). The red arrows show the direction of fatigue crack propagation in location (**B1**) and location (**B2**). The fatigue striations were observed in SE images in areas marked in yellow, and the microstructure details are shown in the **middle** and **upper** panels. In Zone (**C**), the fracture surface is very rough and angular. The fracture surface shows several secondary cracks that are perfectly straight and short. Next to these flat cracks, larger secondary cracks can be seen, which are branched and longer than the flat ones. The lower SEI shows the crack propagation and the **middle** and **upper** SEI shows the details at higher magnifications. The SE image of Zone (**D**), marked in green, shows a sudden fracture. Zone (**D**) in the **right** panel shows areas of EDS analysis of the fracture surface (yellow squares marked in the **right** panel).

In the zones marked B1 and B2, in Figure 4 (main inside panel), gradual fatigue crack progression is visible, and the main direction of crack progression is also marked with red arrows. Traces of the gradual progression of the crack at slightly higher magnifications using a scanning electron microscope are shown in panel B1, marked in yellow. Smaller secondary cracks are also present on the fracture surface, which were formed during the gradual progression of the main crack. The topography of the fracture is rounded, which is an indication that the crack was present for a long time and that during use, there was regular mutual contact between the two parts of the implant, which led to wear and, as a result, a smooth fracture surface [14].

In Zone C, the fracture surface is very rough and angular. The fracture surface shows several secondary cracks that are perfectly straight and short. Next to these flat cracks, larger secondary cracks can be seen, which are branched and longer than the flat ones. Based on the microstructure of the CoCrMo alloy, it can be concluded that the straight and short cracks originated at the twin boundaries (deformation twins in the microstructure) and ended at the crystal grain boundaries. Longer and branched cracks, however, run along the crystal boundaries and the boundaries between the carbides and the matrix [14].

Due to crack propagation, the loads on the diminishing cross-section of the modular neck increased. When the remaining nonfractured area was too small, the rest of the material suddenly fractured. The fracture surface is shown in Figure 4, Zone D, marked in green. The marked yellow rectangles represent areas of EDS analysis. EDS analysis of the fracture surface showed that there was indeed some transfer of Ti from the Ti6Al4V part of the prosthesis to the CoCrMo part. The results of the EDS analysis are given in Table 4. EDS analysis confirms the dissolution of Co into the soft tissue, which is evident from the low content of cobalt on the fracture surface. The same observation is reported in the literature where cobalt is present in the serum, erythrocytes, and urine of patients caused by MoM (metal-on-metal) joints [26].

Table 4. EDS elemental analysis of spectra from the areas marked in Figure 4 (mass %).

Spectrum	C	O	Si	Ti	V	Cr	Mn	Fe	Co	Mo
1	3.9	5.5	0.8	4.7	0.0	26.7	0.0	0.9	50.9	6.2
2	4.5	7.4	0.5	6.3	0.0	26.7	0.0	0.0	48.4	6.2
3	1.3	6.7	0.0	28.0	1.9	27.3	0.0	0.0	34.7	

The upper half of Figure 5 shows the SE image of the CoCrMo microstructure, which was found under the fracture surface. For this purpose, a sample 15 mm below the fracture surface was cut and the metallographic sample was prepared by classic metallographic preparation methods, as described in Section 2.4. The brittle $Cr_{23}C_6$ carbides are embedded in the tough CoCrMo matrix. The fracture surface exhibits the cracked carbide $Cr_{23}C_6$, determined using EBSD–Kikuchi lines, as seen in the lower half of Figure 5. In addition to fretting and crevice corrosion, modular neck stems made of different alloys also suffered galvanic corrosion [23,26]. Our previous studies determined that the CoCrMo passive layer is thinner than the passive layer of the Ti6Al4V alloy and that CoCrMo is vulnerable to crevice corrosion on the surface due to the carbide formation and depletion of Cr [13].

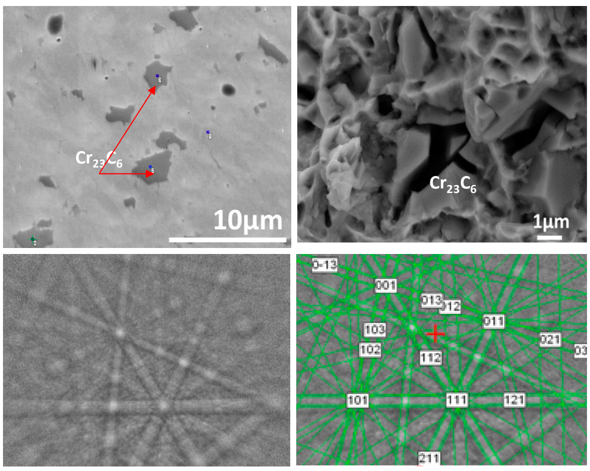

Figure 5. SE image of CoCrMo microstructure. The sample was cut 15 mm under the fractured surface. Matrix hcp structure is light gray, and brittle $Cr_{23}C_6$ carbide is dark gray. The fractured surface exhibits the cracked carbide $Cr_{23}C_6$ determined by the EBSD method by Kikuchi lines.

EDS results show the transfer of Ti ions from the stem to the CoCrMo neck, where Spectrum 3 shows an unexpectedly high titanium content (28.0 mass%) and, vice versa, a very low content of Co (34.7 mass%). According to Gilbert [26], the preferential dissolution of Co and the formation of intermetallic-phase Ti-CrMo occurred.

3.2. Modular Neck Stem Made of the Same Alloy: Ti6Al4V (Neck) and Ti6Al4V (Stem)

The patient with the implanted hip endoprostheses with a long modular neck stem manufactured from the same alloy (both the long modular neck and the stem were made of forged Ti6Al4V alloy) was an active 42-year-old male with a normal BMI. He felt a sudden pain in the hip and heard a crack from that region, and afterward, he was unable to stand. X-rays confirmed a fractured Ti6Al4V neck and required urgent revision surgery (Figure 2, right panel). The survivorship of the modular stem neck was 84 months (7 years).

The fracture surface of the Ti6Al4V neck is shown in Figure 6. The crack initiation site is marked by a green arrow, and the red arrows represent the direction of fatigue crack propagation.

Figure 6. SLM image of the fractured modular neck made from Ti6Al4V alloy, taken from a 42-year-old male, lifetime 84 months. See the text for a description of the arrows.

With the increased stresses on the modular neck stem interface, passive oxide layers of Ti6Al4V are interrupted and re-passivation of the metal surface is prevented due to poor oxygen supply, which causes the release of chloride ions within the joint, and the consequence is a lower local pH. An anaerobic and acidic environment is created, and further abrasive wear and corrosion increase the risk of modular neck fracture over time [12,13,21,24–26].

The combined effects of corrosion, long modular necks, metal-on-metal components, patient obesity, as well as metallic, ceramic, corundum, and polyethylene wear particles and activity levels may create a local microenvironment that can initiate crack formation. During the loading of the same Ti6Al4V neck/Ti6Al4V stem metal system, the crack site of the long modular neck slowly and gradually advanced. Micro-motions at the interface induce fretting and crevice corrosion, contributing to micro-crack creation within the zone of corrosion and increasing the risk of dynamic fatigue fracture.

The part of the fractured surface was covered with organic material of ultra-high-molecular-weight polyethylene (UHMWPE) nanoparticles. The load on the rest of the cracked modular neck increased and traces of gradual crack progression appeared. When the remaining nonfractured area was too small, the rest of the material suddenly fractured.

Figure 7 shows the fractured surfaces on the Ti6Al4V long modular neck (a), where two different regions are found on the fractured surface; the first one is marked with a yellow square (b), and the second is marked with a green square (c). The first region shows signs of mechanical deformation due to walking, and in that region, signs of gradual crack propagation are visible at higher magnification where fatigue striations are seen in the range of 50–100 nm steps (d and e). The second region (a–c) shows the surface of the sudden fracture where a rough and uneven ductile fractured surface is seen with visible ridges and dimples, indicating tearing and deformation of material before the final fracture.

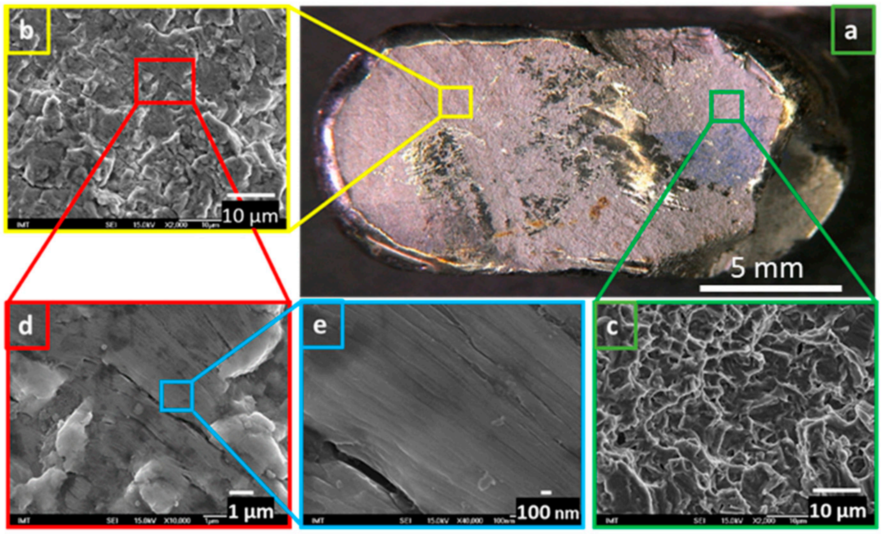

Figure 7. (**a**) Image of different fractured surface regions of fractured Ti6Al4V modular neck; (**a–b**) yellow-marked region and yellow-framed SE image of fatigue failure and with higher magnifications (**b**,**d**,**e**); (**a**,**c**) green-marked region and green-framed SE image with sudden ductile fracture. Organic deposits on fractured Ti6Al4V surface due to PE nanoparticle migration were found and visible as blue color (**a**).

4. Discussion

The use of modular femoral stems in total hip arthroplasty has increased in popularity over the past three decades. Although it offers several distinct advantages intraoperatively, long-term success has not yet been established. The potential complication of increasing modularity is modular neck fracture [3–11,14,17–20].

The results of our studies on the mechanisms of premature modular neck fracture of different and same alloys showed that fretting, corrosion, and fatigue occurred on both neck–stem retrievals of the same Ti6Al4V neck/Ti6Al4V stem alloy, as well as different CoCrMo neck/Ti6Al4V stem alloys where galvanic corrosion was also involved, which is in good agreement with literature data [21–27].

Our findings are in good agreement with Ref. [24], where Virtanen reports that for orthopedic implants, fretting corrosion (or generally, wear-assisted corrosion/tribo-corrosion) is often discussed as the dominant failure mode, especially in the case of high-corrosion-resistance passive alloys, for which the tribological load leads to local mechanical destruction of the passive film. Even though a subsequent spontaneous re-passivation reaction takes place in many cases, continuous activation/re-passivation cycles lead to an increased material loss. Virtanen reported that the fretting corrosion behavior and restoration ability were studied under various combinations of load, frequency, and number of fretting cycles and that the thickness and the nature of oxide–passive layers on Ti strongly influence the mechanism and the intensity of tribo-corrosion. The degradation of biomaterials in the biological environment is a complex process that depends on all material parameters (e.g., chemical composition, microstructure), environmental parameters (e.g., chemistry, temperature), as well as construction (e.g., presence of crevices). For materials in biomedical applications, the situation is more complex than in classical engineering applications because the biological environment of the host is a highly dynamic system [24].

In the case of a stem and neck composed of different alloys, Ti6Al4V and CoCrMo, the hip endoprosthesis designers ignore the fact that Ti6Al4V and CoCrMo have different electrochemical potentials which, after implantation, are immersed in a corrosive electrolyte, human liquids. Besides fretting, fatigue and corrosion occurred. The corrosion is usually crevice corrosion, but galvanic corrosion also occurred. This caused the formation of corrosion damage on the surface, and everyday normal activity due to dynamic loading leads to the formation of microcracks on the surface which then gradually propagate. No excessive mechanical loadings were needed since crack tips are usually very sharp and stress concentrations are consequently high enough to cause the crack to propagate. Once the remaining cross-section of the implant is diminished, it can no longer support the loads, leading to a catastrophic break [21–24]. This statement is in good agreement with the survivorship of the modular neck stem of different alloys, which was only 24 months in our case study.

The main aim of our studies was to emphasize the importance of the optimal choice of materials for the modular neck stem of hip endoprostheses. To emphasize the importance of the materials, two cases of failed modular neck stems, which we received from two hospitals (a university clinical center and a community hospital), were studied.

Both metal systems of different alloys, CoCrMo/Ti6Al4V, and the same alloy, Ti6Al4V/Ti6Al4V, were immersed after implantation into a corrosive electrolyte, human liquids, and exposed to constant micromotion, leading to fretting and corrosion, but the system of different alloys suffered more corrosion due to additional galvanic corrosion due to different electrochemical potentials [26].

The neck and stem composed of the same material, Ti6Al4V, have the same electrochemical potential and the prosthesis is still immersed in body liquids and electrolytes. In this case, the initial crack formation can be slower and is not the consequence of corrosion damage, but occurs due to fretting and wear corrosion [19,20,22,24,26,27]. Again, the crack propagates by everyday normal activity, where each step represents the dynamic cycle of loading and causes the crack to slowly propagate. When the nominal cross-section of the implant is diminished to such an extent that the remaining cross-section can no longer support the load, catastrophic failure occurs. This statement is in good agreement with the survivorship of the modular neck stem of the same Ti6Al4V/Ti6Al4V alloy, which was 84 months in our case study.

The recent literature data on survivorship of the modular neck stem THA system confirm a lower yield than the similar mono-block stem THA system in a comparable clinical environment with long-term follow-up [28–33].

5. Conclusions

We found that fretting, corrosion, and fatigue occurred on both neck–stem retrievals of the same (Ti6Al4V neck/Ti6Al4V stem) and different (CoCrMo neck/Ti6Al4V stem) metal systems.

The cracked femoral neck made of CoCrMo alloy was dynamically loaded, exposed to a corrosive medium, and surrounded by a Ti6Al4V alloy with a different electrochemical potential. Due to the constant dynamic load and a combination of different materials in a corrosive medium, galvanic corrosion on the surface of the modular neck occurred.

The different-metal system made of CoCrMo/Ti6Al4V suffered more corrosion than the same-metal system made of Ti6Al4V/Ti6Al4V alloy due to additional galvanic corrosion.

The nature of the in vivo mechanisms causing the formation of the bio-tribo-corrosion processes needs to be understood and characterized so that appropriate changes in design and materials can be implemented.

Investigations of retrieved modular hip implants have revealed that significant corrosion can occur in vivo over the long term and may be a significant contributor to adverse biological effects and clinical failure seen in some patients (third body wear, remote trace metal accumulation, aseptic loosening, etc.), bringing into question the concept of modularity.

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