

Editorial

Failure Analysis of Biometals

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Received: 30 April 2020; Accepted: 15 May 2020; Published: 19 May 2020



1. Introduction and Scope

Metallic biomaterials (biometals) are widely used for the manufacture of medical implants, ranging from load-bearing orthopaedic prostheses to dental and cardiovascular implants, because of their favourable combination of properties including high strength, fracture toughness, biocompatibility, and wear and corrosion resistance. Additionally, they can be fabricated using well-established techniques (such as casting and forging), and recently, additive manufacturing to produce complex and customised implants. Examples of metals and metal alloys that are used for the fabrication of implants include the following: Ti-based alloys (e.g., Ti6Al4V and Ti6Al7Nb), Co-based alloys (e.g., CoCrMo and CoNi), austenitic stainless steels (e.g., SS316L), Zr-Nb alloys, Ni-Ti Alloys, Mg alloys, porous tantalum foams, and precious metals and alloys.

Owing to the significant consequences of implant material failure/degradation, in terms of both personal and financial burden, failure analysis of biometals (in-vivo, in-vitro, and retrieval) has always been of paramount importance in order to understand the failure mechanisms and implement suitable solutions with the aim to improve the longevity of implants in the body. This Special Issue presents some of the latest developments and findings in the area of biometals failure including fatigue, fracture, corrosion, and fretting wear on a range of conventional biometals as well as porous materials and new generation titanium alloys.

2. Contributions

The Special Issue “Failure Analysis of Biometals” comprises ten original research articles [1–10] covering a great common range of metallic biomaterials (Ti alloys, CoCrMo alloys, Mg alloys, NiTi alloys) and their failure mechanisms (corrosion, fatigue, fracture, and fretting wear) that commonly occur in medical implants and surgical instruments. This collection of studies also includes two review papers [9,10]: the corrosion behaviour of new generation low modulus titanium alloys for implant applications, and the three-dimensional (3D) printed acetabular cups for hip replacement implants reviewing the clinical use of 3D printing in orthopaedics.

Starting with research articles, Alqedairi et al. [1] studied the cyclic fatigue behaviour of endodontic rotary files made of nickel titanium (NiTi) alloys. Owing to the cyclic rotation of this dental instrument within the curved canal, fatigue fracture can occur over time. The failure can be either flexural or torsional in its loading nature. Three different rotary instruments including ProTaper Universal (PTU), ProTaper Gold (PTG), and ProTaper Next (PTN) were assessed in this work. Artificial canals were machined in stainless steel blocks. Fifteen rotary instruments of each type (five types of PTU and PTG and three types of PTN) were rotated with 300 rpm until fracture. Weibull reliability analysis and the probabilities of survival calculated for the PTU, PTG, and PTN instruments showed the PTG series to offer a higher reliability than the PTU and PTN series. The PTG instruments were found to have a superior cyclic fatigue behaviour when compared with the PTU and PTN series. The higher fatigue resistance of the PTG and PTN instruments was attributed to the thermomechanical treatment performed on the NiTi alloy of these instruments. Fatigue is understood to be the most common failure mechanism in rotary

instruments; therefore, international standards for testing against fatigue failure of these medical devices should be established in order to reduce considerable differences in their behaviour.

In a two-part study conducted by Goswami and co-authors [2,3], the failure of a stainless steel 316 L proximal humerus internal locking system (PHILOS) plate and screws, which had been used for a pantalar arthrodesis, was investigated. The research employed both experimental (SEM/EDS, microstructural analysis using electron backscatter diffraction (EBSD), hardness tests, and fractography) and computational (finite element modelling) approaches. The results of fractography, particularly SEM investigations, indicated the occurrence of corrosion fatigue failure initiated by crack initiations in the distal region of the steel plate, leading to crack propagations towards the proximal region and a final brittle fracture. Crack initiations in the plate were reported to be the result of the inclusions and corrosion pits. The failure of the screws was because of overloading, which occurred ahead of the plate from the proximal end. Finite element analysis (FEA) on the implant system, implemented using ANSYS, showed increased von Mises stresses in the cortical screws as the angle between the screws and the plates increased. Moreover, the stress magnitudes were found to be lower (by 25.5%) in the locking screws when compared with the cortical screws, which was understood to be because of the fixed angles of the locking screws onto the plate (less range of motion).

Returning the focus again to nickel titanium alloys in this Special Issue, the *in vitro* corrosion assessment of porous NiTi structures was studied by Ibrahim et al. [4] for bone fixation applications. The structures were fabricated by additive manufacturing, which is expanding very rapidly nowadays. It is, however, noted that additively manufactured NiTi structures still have some issues such as poor surface quality and presence of impurities and defects. Employing the selective laser melting (SLM) technique, NiTi samples in both the bulk and porous forms (porosity levels of 15–50%) were fabricated. The electrochemical corrosion characteristics of these SLM NiTi samples were found to be similar to those of conventionally fabricated NiTi samples. The 50% porous structures showed the highest Ni ion release level owing to their biggest surface area exposed to the corrosive environment. The main finding in this work was that the SLM manufacturing process employed to fabricate NiTi structures for bone fixation applications did not cause a significant deterioration in their corrosion resistance.

In medical implants, where there is contact between the implant material and living bone, a stable implant–bone interface is essential for clinical success of fixation by osseointegration and bone ingrowth. A second important factor vital for achieving success is that there be a minimal mismatch between the mechanical properties of the implanted prostheses and the host skeleton. If there is a substantial discrepancy between the said properties, significant stress shielding can occur, causing adverse effects on the implant and/or the host skeleton. Additive manufacturing can be wisely employed to fabricate stiffness-modulated implants to minimise stress shielding failure, which is one of the interesting areas of research at present. In a study by Jahadakbar et al. [5], bone fixation plates were designed and manufactured out of NiTi alloys using additive manufacturing (SLM method), such that the stiffness of the Nitinol plates was modulated. Five different porosity levels (17%, 20%, 24%, 27%, and 30%) as well as a bulk plate (0% porosity) were designed and analysed using finite element modelling (Abaqus software), showing a good agreement with the experimental results of mechanical testing. Following the model verification, Ni-rich fixation plates were manufactured, offering a superelastic behaviour. Differential scanning calorimetry (DSC) was employed in order to identify the transformation temperatures (TTs) from -90 to 100 °C in a nitrogen atmosphere. The DSC results showed a small variation in the transformation temperature of different points in the fixation plates owing to the various thermal histories that the complex plates experienced during the additive manufacturing process. A post-processing heat treatment may thus be required in order to achieve homogeneity in the as-fabricated parts.

Magnesium (Mg)-based alloys exhibit biodegradable and biocompatible characteristics, enabling them to be used in degradable implants that can dissolve in the body after the treatment of a medical condition. However, there are still a number of aspects that need to be further researched and addressed (e.g., mechanical and corrosion properties and degradation behaviour). Taking into account that

calcium (Ca) is an important element in the bone structure, Chen et al. [6] developed a magnesium-based alloy (Mg-1Ca-0.5Zr) using casting. Zirconium (Zr) was also added to enhance the grain refinement in the alloy. The main aim was to assess the mechanical properties and surface corrosion mechanism in the developed alloy. A heat treatment (400 °C for 8 h, followed by quenching in water) was applied to the alloy to improve its mechanical properties. In addition to tensile tests, erosion wear tests were performed on the alloy samples with and without the heat treatment. Moreover, a potentiodynamic polarization test was performed on these samples and a pure Mg sample. The heat treatment was found to enhance the ductility and reduce the corrosion rate of the alloy. Moreover, it was reported that the Mg alloy subjected to the heat treatment formed a protective calcium phosphate film when immersed and tested in a simulated body fluid. This protective layer decreased the corrosion rate considerably.

In an investigation on retrieved total hip replacement implants, particularly the metallic taper junction known as the head–neck junction, corrosion damage to the neck part of 137 femoral stem implants was analysed using the Goldberg’s scoring method [7]. The studied stems were made of three biometals including CoCrMo, stainless steel (SS), and titanium alloy. The neck surface was divided into eight distinct zones to statistically study the distribution and severity of corrosion damage. The distal region was found to have more corrosion damage compared with the proximal region of the neck. The most severe corrosion also occurred in the medial distal zone. This study suggests that retrieval studies of head–neck taper junctions should assess the corrosion damage in various zones of metallic implants separately.

In the same area of the head–neck taper junction in hip implants, Fallahnezhad et al. [8] studied material loss as a result of fretting wear with a focus on the role of assembly force (impaction force applied by surgeons to assemble the junction intraoperatively). Both the head and neck components were made out of CoCrMo alloy, with an angular mismatch of 0.01°. Developing an adaptive finite element model for fretting wear, four assembly forces (2, 3, 4, and 5 kN) were applied to the junction followed by a walking gait loading (1,025,000 cycles). The results showed the direct effect of assembly force; the higher the force, the greater the material removal owing to fretting wear. It was discussed that a high assembly force can generally improve the stability of the junction; however, it may also enhance the wear damage to the material. This study did not include corrosion in the simulations; thus, further research is suggested to create novel models to capture both fretting wear and corrosion simultaneously.

In a review on the clinical use of 3D printing (additive manufacturing) in orthopaedics, Dall’Ava et al. [9] focused on titanium acetabular cup implants used in total hip replacement, where they compared 3D printing with conventional manufacturing. This review defined the rationale of additively manufactured acetabular cups from both the clinical and engineering perspectives. A number of interesting aspects associated with the topic were discussed and summarised. These include the key manufacturing-related variables that can have an influence on the characteristics and properties of the fabricated implants, and the limitations associated with this manufacturing technology. Additively manufactured titanium cups have presented promising early clinical outcomes. It is, however, important to note that more detailed studies are still needed to look at their failure and long-term performance in the body.

Finally, this Special Issue presents a review article [10] on the corrosion behaviour of new generation titanium alloys (β -type offering low Young’s modulus) that can be desirably used for medical implants.

There are some existing concerns about the toxicity of the two alloying elements (aluminium and vanadium) in the most commonly used titanium alloy in medical applications (Ti-6Al-4V). Furthermore, the stiffness (Young’s modulus) of this alloy, which is approximately 110 GPa, is much higher than the typical stiffness of the bone (10–30 GPa). This can result in stress shielding under the loads of physical activities and, consequently, prosthesis loosening, bone loss, and fracture failure. To address these issues, extensive research has been done to develop new generation β -type titanium alloys with lower levels of stiffness. These alloys contain beta-stabilising elements, for example, Nb, Ta, and Zr, which are also non-allergic and non-toxic. Although there has been a lot of work around the

improvement of mechanical properties in these alloys, their corrosion behaviour still needs further research (given that the implant working environment is corrosive). In this article, Afzali et al. [10] reviewed and discussed a number of key factors (fabrication process, chemical composition, passive layer, mechanical treatments, body electrolyte properties, and constituent phases) influencing the corrosion behaviour/resistance of new generation titanium alloys. The effects of α and β phases and their dissolution rates on the oxide layer and corrosion behaviour were also reviewed. It was recommended that the microstructure of these new generation alloys should contain suitable amounts of α and β phases to achieve a high corrosion resistance, as well as a stable oxide layer.

3. Conclusions

Failure Analysis of Biometals presents a collection of studies covering a wide range of failure mechanisms in medical implant materials. The contributions reflect the profound interest in this area aiming to address current issues in biometals, manufacturing techniques, and implant applications, while employing various research methodologies. Challenges still remain, however, there are also great opportunities for research to better analyse and understand failures in biometals and come up with successful engineering solutions.

Acknowledgments: As Guest Editor, I would like to thank all the researchers who contributed their work to this Special Issue; and also, the reviewers who provided feedback to improve the quality of the articles. I would also like to thank the MDPI *Metals* Editorial Team, especially the Managing Editor Mrs. Sunny He, for their great management and support in the publication process.

Conflicts of Interest: The author declares no conflict of interest.

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