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Understanding Aluminium Ion Release from Ti6Al4V 3D-Printed Implants for Long-Term Biocompatibility

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Abstract

Due to its remarkable strength-to-weight ratio, corrosion resistance, and biocompatibility, Ti6Al4V has become one of the most popular titanium alloys for implants in the human body. Additive manufacturing also helps in further revolutionizing the field by enabling patient-specific implants with intricate design. However, tribocorrosion poses a threat to long-term biocompatibility of the implants. Studies revealed that in a more acidic environment, higher levels of aluminium ions will be released into the environment, raising serious concerns about the effects of long-term exposure to aluminium. Research suggests that surface treatments can slightly reduce the release, as shown in study conducted by Orlowska et al. [1] who found that the amount of aluminium ions released from a sample modified using plasma electrolytic oxidation (PEO) was almost 20% lower than that of an unmodified sample. This shows that surface treatment plays a critical role in providing longer-lasting implant performance.

Keywords: 3D printing, additive manufacturing, corrosion, surface treatment, Ti6Al4V

1 Introduction

Ti6Al4V alloy, which comprises 90% titanium, 6% aluminium, and 4% vanadium, has become the gold standard for biomedical implants due to its excellent blend of mechanical strength, corrosion resistance, and biocompatibility. Compared to other metallic materials such as stainless steel or cobalt-chromium alloys, Ti6Al4V has an elastic modulus that is closer to the human body, which helps reduce stress shielding which can result in bone resorption [2]. This alloy can also sustain decades of cyclic loads without failing due to its exceptional fatigue resistance and strength-to-weight ratio. Moreover, this metal produces a stable, self-healing layer of titanium dioxide on its surface that promotes osseointegration and provides strong corrosion resistance in the saline environment of bodily fluids.

The design and production of Ti6Al4V implants in the biomedical industry have been completely transformed by the development of additive manufacturing or 3D printing techniques, especially laser powder bed fusion (LPBF) and electron beam melting (EBM) [3][4]. These techniques enable the production of extremely intricate, patient-specific geometries that guarantee ideal fit and load distribution. It is also easier to create regulated porosity structures that resemble the natural human bone, which encourages improved bone ingrowth. The ability to create gradients in porosity and mechanical characteristics represents a paradigm shift in orthopaedic surgery, transforming implants from straightforward mechanical replacements into bioactive, patient-specific structures that actively support healing and integration.

Despite these advantages, there are increasing concerns regarding the long-term biocompatibility of Ti6Al4V, particularly with regard to the release of aluminium ions from the implants over prolonged use in the body. Although the protective oxide layer offers some protection, the implant will experience ongoing low-level degradation due to wear and corrosion in the harsh physiological environment [5]. Aluminium will gradually leach as a result of this degradation and can create serious concerns such as inflammatory reactions and possible neurological consequences. To guarantee the long-term safety of 3D-printed Ti6Al4V implants, it is essential to address this aluminium release issue, and in this paper, the strategy to mitigate this will also be discussed.

2 Mechanisms of Ion Release from Ti6Al4V Implants into the Human Body

The long-term interaction between Ti6Al4V alloy and the environment can cause the gradual release of ions, despite the alloy's high corrosion resistance. The main mechanism is corrosion involving passive film disruption, in which the body's aggressive biochemical environment can compromise the protective titanium dioxide layer. Studies have shown that under inflammatory conditions, the local pH can drop under 5.5, producing a more acidic environment. This can accelerate corrosion and tear down the oxide layer locally, as seen in Figure 1 [6]. Aluminium is more prone than titanium to preferential dissolution, which results in its release as free Al^{3+} ions. Additionally, the alloy's microstructural heterogeneity, which consists of alpha phase (aluminium-rich) and beta phase (vanadium-rich) regions with varying electrochemical potentials, can create micro-galvanic couples that encourage the preferential dissolution of aluminium-rich regions.

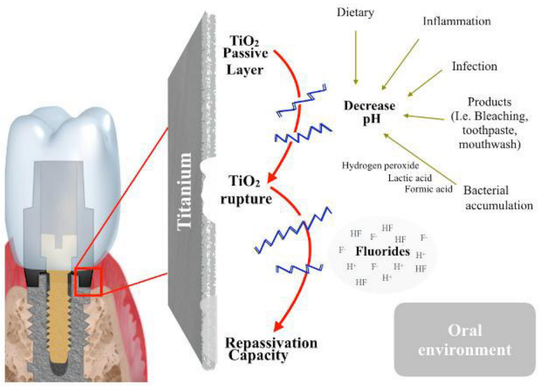

Figure 1. Factors that affect the corrosion behavior of the titanium [7]

Triborrosion, which is an interplay between chemical corrosion and mechanical wear, is the most important and inevitable cause of aluminium release. At implant-bone contacts or between modular components, repetitive mechanical stress results in fretting, revealing highly reactive metal surfaces. In the presence of bodily fluids, these recently exposed surfaces instantly try to repassivate by forming new oxide layers. This results in a continuous cycle of mechanical damage followed by chemical repassivation, which increases material loss significantly [8]. With every cycle of motion, this mechanism releases metallic ions and nanoscale particles in addition to micron-sized wear debris, especially at modular junctions like screws in spinal structures. According to Kumar and Thakur [9], worn debris and released ions can cause inflammatory reactions and activate macrophages, which in turn release acidic chemicals that further accelerate corrosion. Defects in the oxide layer can also trigger localized corrosion mechanisms such as pitting or crevice corrosion, resulting in active anodic patches where metal dissolves quickly.

Aluminium ions travel different routes after being discharged, which may have biological repercussions. Aseptic osteolysis, a chronic inflammatory response that causes bone resorption and ultimately implant loosening, may result from the local accumulation of Al^{3+} ions in periprosthetic tissue. Besides, aluminium ions can also attach to plasma proteins and travel through blood streams to distant organs such as the kidneys and liver. Aluminium can also bind to phosphate groups in biological molecules, impair bone remodelling, and interfere with calcium-dependent activities. Although direct causality in orthopaedic implants has not been proven, the neurotoxic potential of aluminium is especially concerning due to its capacity to cross the blood-brain barrier, accumulate in neural tissue, and have associations with neurodegenerative conditions. Research has shown that aluminium is among the most widely distributed metals from the implants into the human body [10]. This indicates a crucial need for surface modifications for long-term biocompatibility of the implants.

3 Surface Treatment Strategies to Mitigate Ion Release

The focus of research in this field has shifted to developing surface treatment techniques that produce strong and stable barriers that outperform the native titanium dioxide layer in order to address the problem of aluminium ion release while maintaining the mechanical advantages of Ti6Al4V. The primary goals are to seal the aluminium-containing substrate from the physiological environment, promote rapid osseointegration to create a stable seal that further isolates the implant, and significantly improve the corrosion and wear resistance of the implants. According to Table 1, surface treatments can maintain the mechanical properties of Ti6Al4V while significantly changing the surface chemistry to reduce ion release into human body.

Table 1. Comparison of surface treatments that can be done

Surface Treatment	Mechanism	Findings	Limitations / Considerations	Ref
Anodic Oxidation	- Thickens the oxide film; can produce nanoporous or nanotubular TiO_2 structures - Creates dense diffusion barrier	- Enhanced corrosion resistance - Improved cell response - Can anchor subsequent coatings	- Nanotubes may detach under heavy mechanical load - Some phases less stable in vivo	[11]
Plasma Electrolytic Oxidation (PEO) / Micro-Arc Oxidation	- Creates thick, microporous, crystalline oxide layers integrated with substrate - Incorporates Ca, P, Si, Sr into oxide matrix	- Excellent corrosion protection - Microporosity allows bone ingrowth; creates mechanical interlock - Reduces micromotion and fretting	- High-voltage process requires specialized equipment - Surface roughness may need post-processing	[12]

Bioactive Glass / Ceramic Coatings	- Forms bioactive apatite layer in vivo - Ceramic component increases bioactivity	- Strong bonding with bone - Improved chemical stability - Can include therapeutic dopants (Mg, Si)	- Brittle - Mechanical mismatch may cause cracking - Adhesion depends on pre-treatment	[13]
Plasma Nitriding / Titanium Nitride (TiN) Coatings	- Forms hard TiN/Ti_xN layers - Diffuses nitrogen into surface - Increases surface hardness - Reduces fretting wear	- Dramatically improves wear and corrosion resistance - Stable chemically - Gradual transition to base alloy avoids delamination	- High processing temperature - Risk of distortions in thin structures - May require post-processing	[14]
Laser Remelting	- Removes microdefects and porosity - Increases grain-boundary density - Improves passivation layer	- Improves fatigue, corrosion, and wear properties - Removes partially fused particles - Lower corrosion currents	- Requires precise control - May alter microstructure undesirably if over-processed - Surface finish may still require polishing	[15]

Since no single surface treatment can meet every need at once, multi-layer treatments may produce the best long-term results. Past studies indicate that different post-processing methods have a significant impact on coating adhesion [16]. Combining these with laser melting and nitriding or anodization, may be very helpful for load-bearing 3D-printed implants. In order to limit micromotion and wear over time, these multi-layer treatments seek to remove surface defects that can cause corrosion, generate stable layers, form biocompatible barriers that stop ion diffusion, and promote osseointegration. The trade-offs between corrosion protection, mechanical integrity, manufacturing complexity, and cost must be carefully considered when choosing the best methods, which also vary depending on the implant application.

4 Conclusion

Over the course of several decades, Ti6Al4V has been widely used in the biomedical industry due to its remarkable mechanical performance and biocompatibility. Additive manufacturing also allows for truly personalized application through patient-specific geometries and porous architectures that encourage bone ingrowth. But there has been growing concern regarding the long-term impact of aluminium ion release from the implants through tribocorrosion and passive film disruption. By separating the alloy's mechanical advantages from its electrochemical weaknesses, advanced surface engineering techniques provide the most practical solution. These methods include anodic oxidation to fortify the native oxide layer, the formation of integrated bioactive layers via PEO, and surface hardening through nitriding. The most promising treatments are multi-layered ones that combine various methods and may include self-healing properties for long-term protection. Future research direction require combining the geometric freedom of additive manufacturing with surface engineering, supported by strict long-term clinical validation and standardized treatment protocols for 3D-printed implants. By mastering the bio-interface through intentional surface modification, Ti6Al4V implants can be expected to meet the highest standards of patient safety and implant longevity while fulfilling the promise of customized treatment.

5 References

[1] Orłowska, A., Kajzer, W., Goldsztajn, K., Gawron, A., Godzierz, M., Nowińska, K., ... & Szewczenko, J. (2024). Functionalization of 3D printed Ti6Al4V high-porous spinal implant surface with use of plasma electrolytic oxidation. *Applied Surface Science*, *659*, 159948. DOI: 10.1016/j.apsusc.2024.159948

[2] Koju, N., Niraula, S., & Fotovvati, B. (2022). Additively manufactured porous Ti6Al4V for bone implants: a review. *Metals*, *12*(4), 687. DOI: 10.3390/met12040687

[3] Ahmad Buhairi, M., Mohd Foudzi, F., Jamhari, F. I., Sulong, A. B., Muhamad, N., Mohd Radzuan, N. A., ... & Abd Aziz, I. (2025). Development of a processing window for Ti6Al4V in LPBF: balancing hardness and surface integrity. *Rapid Prototyping Journal*. DOI: 10.1108/RPJ-08-2024-0330

[4] Bandekhoda, M. R., Mosallanejad, M. H., Atapour, M., Iuliano, L., & Saboori, A. (2024). Investigation on the potential of laser and electron beam additively manufactured Ti–6Al–4V components for orthopedic applications. *Metals and Materials International*, *30*(1), 114-126. DOI: 10.1007/s12540-023-01496-6

[5] Neto, M. (2019). *Understanding the wear and tribocorrosion processes and mechanisms of titanium alloys in bovine serum solution* (Doctoral dissertation, University of Sheffield).

[6] Pu, J., Liu, C., Si, Y., Cui, W., Zhang, C., & Song, J. (2025). Tribocorrosion of Metallic Biomaterials under Simulated Inflammation Conditions: Current Status and Future Prospects. *Advanced Healthcare Materials*, e02419. DOI: 10.1002/adhm.202502419

[7] Souza, J. C., Apaza-Bedoya, K., Benfatti, C. A., Silva, F. S., & Henriques, B. (2020). A comprehensive review on the corrosion pathways of titanium dental implants and their biological adverse effects. *Metals*, *10*(9), 1272. DOI: 10.3390/met10091272

[8] Mathew, M. T., & Wimmer, M. A. (2011). Tribocorrosion in artificial joints: in vitro testing and clinical implications. In *Tribocorrosion of passive metals and coatings* (pp. 368-400). Woodhead Publishing. DOI: 10.1533/9780857093738.3.368

[9] Kumar, A., & Thakur, A. (Eds.). (2025). *Biomedical Implant Corrosion Mitigation Through Surface Engineering*. Royal Society of Chemistry.

[10] Tanoğlu, O., Say, F., Yücens, M., Alemdaroğlu, K. B., İltar, S., & Aydoğan, N. H. (2020). Titanium alloy intramedullary nails and plates affect serum metal ion levels within the fracture healing period. *Biological trace element research*, *196*(1), 60-65. DOI: 10.1007/s12011-019-01913-1

[11] Yao, Q., Jiang, Y., Tan, S., Fu, X., Li, B., & Liu, L. (2020). Composition and bioactivity of calcium phosphate coatings on anodic oxide nanotubes formed on pure Ti and Ti-6Al-4V alloy substrates. *Materials Science and Engineering: C*, *110*, 110687. DOI: 10.1016/j.msec.2020.110687

[12] Vangolu, Y. S., Alsaran, A., & Yildirim, O. S. (2025). In vivo behaviour of hydroxyapatite-containing titania coated Ti6Al4V cortical screws by plasma electrolytic oxidation and hydrothermal treatment. *Journal of Alloys and Compounds*, 181665. DOI: 10.1016/j.jallcom.2025.181665

[13] Liang, J., Lu, X., Zheng, X., Li, Y. R., Geng, X., Sun, K., ... & Liu, K. (2023). Modification of titanium orthopedic implants with bioactive glass: A systematic review of in vivo and in

vitro studies. *Frontiers in bioengineering and biotechnology*, *11*, 1269223. DOI: 10.3389/fbioe.2023.1269223

[14] Dwivedi, P., Rane, R., Jhala, G., Ghoroi, C., & Joseph, A. (2025). Electrochemical Corrosion Investigation of Plasma Nitrided Ti-6Al-4V Alloy in Different Simulated Solution. *Journal of Materials Engineering and Performance*, 1-14. DOI: 10.1007/s11665-025-12156-8

[15] Bedmar, J., de la Pezuela, J., Riquelme, A., Torres, B., & Rams, J. (2022). Impact of remelting in the microstructure and corrosion properties of the Ti6Al4V fabricated by selective laser melting. *Coatings*, *12*(2), 284. DOI: 10.3390/coatings12020284

[16] Ebrahimi, M., Kermanpur, A., Kharaziha, M., & Bagherifard, S. (2024). Engineering of multilayered coating on additively manufactured Ti-6Al-4V porous implants to promote tribological and fatigue performances. *Surface and Coatings Technology*, *494*, 131400. DOI: 10.1016/j.surfcoat.2024.131400