

TiO₂ Nanotube-Based Surface Modification of EB-PBF Ti6Al4V: Toward Multifunctional Performance Enhancement

Alireza Moradi¹, Sanae Tajalli², Amir Behjat^{3,4}, Luca Iuliano^{3,4}, Abdollah Saboori^{3,4}

¹ Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

² Department of Applied Science and Technology, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

^{3,4} Department of Management and Production Engineering, Integrated Additive Manufacturing Center (IAM@PoliTo), Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

INTRODUCTION & AIM

This study investigates the anodization behaviour and surface modification of Ti-6Al-4V (Ti64) components produced by electron beam powder bed fusion (EB-PBF) to enhance their biomedical performance. Ti64 samples were fabricated with optimized EB-PBF parameters and anodized at 40 V and 60 V for 2 h to form self-organized TiO₂ nanotube layers, followed by heat treatment at 550 °C. SEM and AFM analyses showed that 40 V produced uniform, compact nanotubes with moderate roughness and higher hardness, while 60 V generated thicker, less ordered nanotubes with greater roughness and slightly reduced mechanical strength. XRD confirmed anatase TiO₂ formation, and EDS indicated uniform Ti and O distribution. Nanoindentation and nanoscratch tests revealed higher hardness and adhesion at lower voltages, while electrochemical measurements showed superior corrosion resistance in anodized samples. In vitro bioactivity tests confirmed enhanced apatite formation, demonstrating that combining EB-PBF with controlled anodization effectively improves the mechanical, corrosion, and biological performance of Ti64 implants.

METHOD

The experimental workflow consisted of three main stages: fabrication of Ti-6Al-4V substrates via EB-PBF, anodization to form TiO₂ nanotube layers, and comprehensive characterization of the modified surfaces.

- **Substrate fabrication:** EB-PBF using an Arcam A2 system with spherical Ti-6Al-4V powder under standard parameters.
- **Anodization:** Conducted at 40 V and 60 V for 2 h in an electrolyte of 90 vol.% ethylene glycol, 9 vol.% deionized water, and NH₄F, followed by heat treatment at 550 °C.

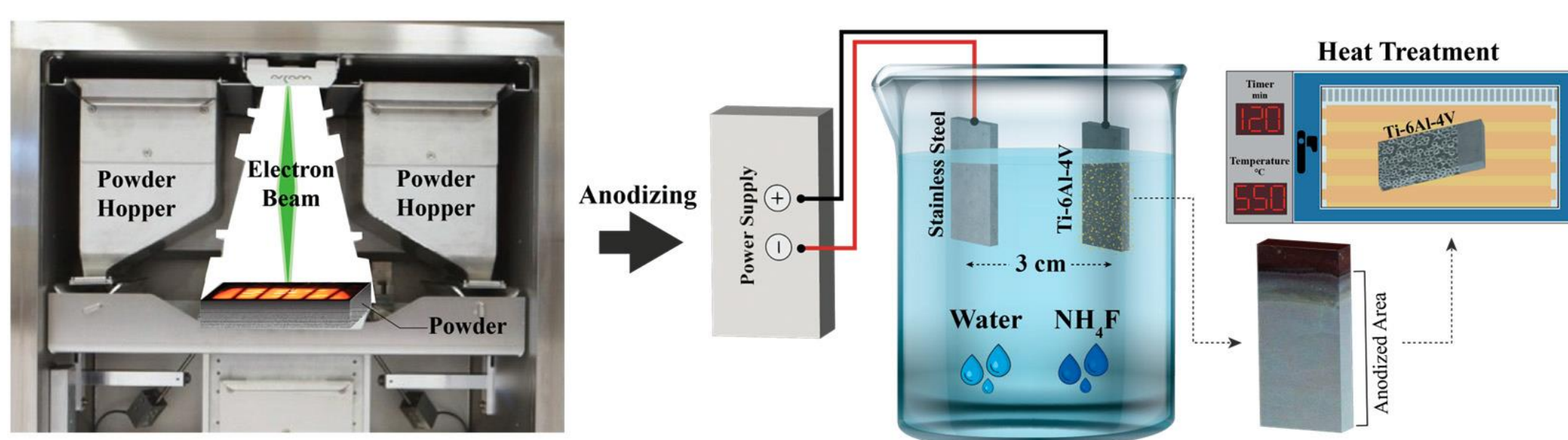


Figure 2. Process flow for fabricating and anodizing EB-PBF Ti64 samples.

- **Characterization:** Surface and structural analyses performed using SEM, XRD, and EDS; topography by AFM; mechanical properties by nanoindentation and nano scratch tests; corrosion behaviour by EIS and PDP in simulated body fluid (SBF); and in-vitro bioactivity assessment via apatite formation.

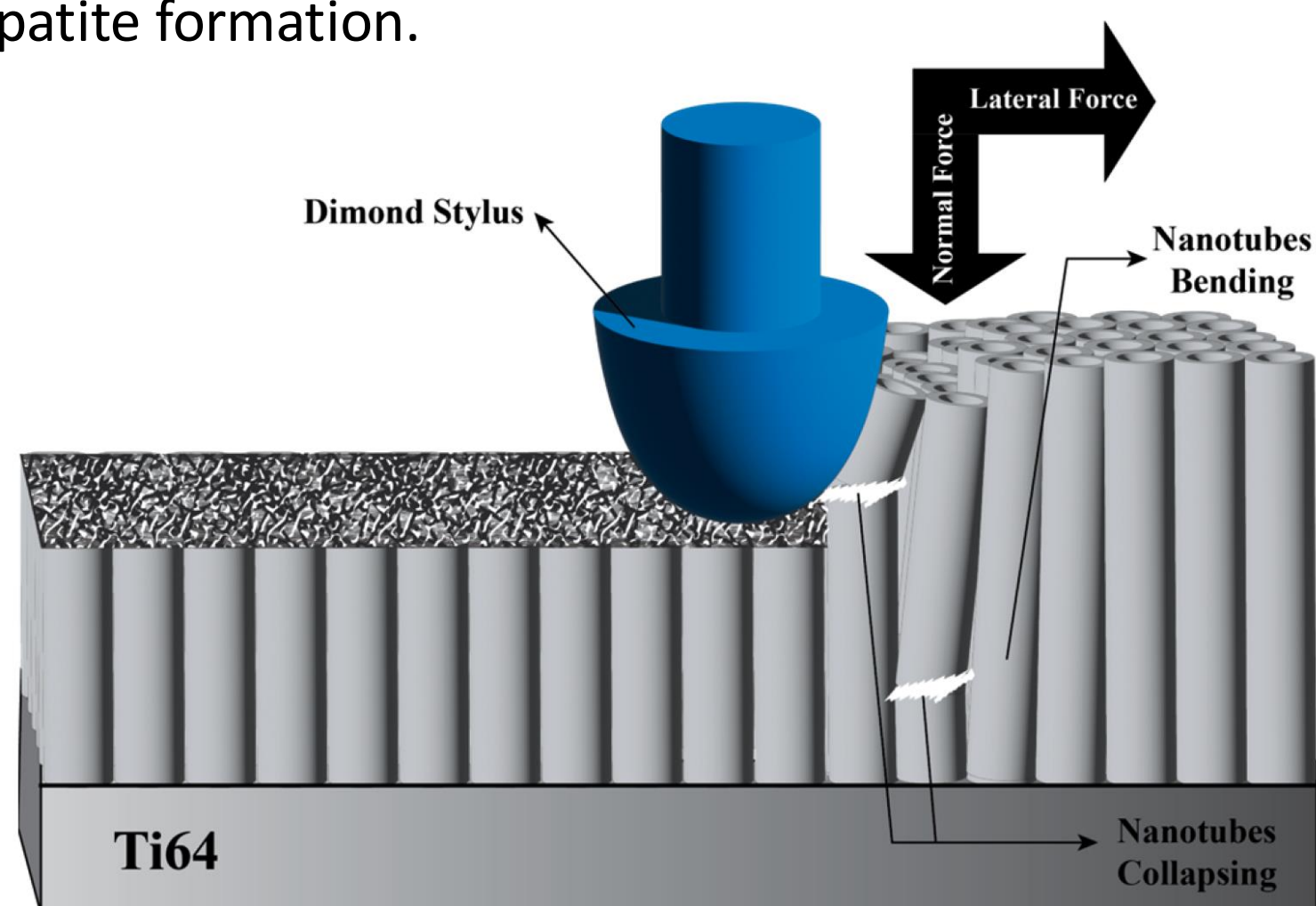


Figure 3. Schematic illustration of the nano scratch test performed on the modified surface.

RESULTS & DISCUSSION

The surface and mechanical properties of anodized EB-PBF Ti64 were systematically characterized to evaluate the effect of anodization voltage on morphology, roughness, hardness, corrosion resistance, and bioactivity. Microstructural analysis confirmed a dense α/α' matrix with uniform composition before anodization. Increasing the anodization voltage from 40 V to 60 V changed the nanotube morphology, resulting in larger, less ordered TiO₂ arrays and higher surface roughness. AFM and nanoindentation results showed that smoother, more compact nanotubes formed at 40 V had higher hardness and elastic modulus. Electrochemical tests (EIS, PDP) showed significantly improved corrosion resistance for both anodized samples compared to the base alloy, with the 60 V sample showing the lowest corrosion current density. In-vitro bioactivity studies demonstrated uniform apatite formation on both surfaces, confirming the enhanced biological potential of the anodized coatings.

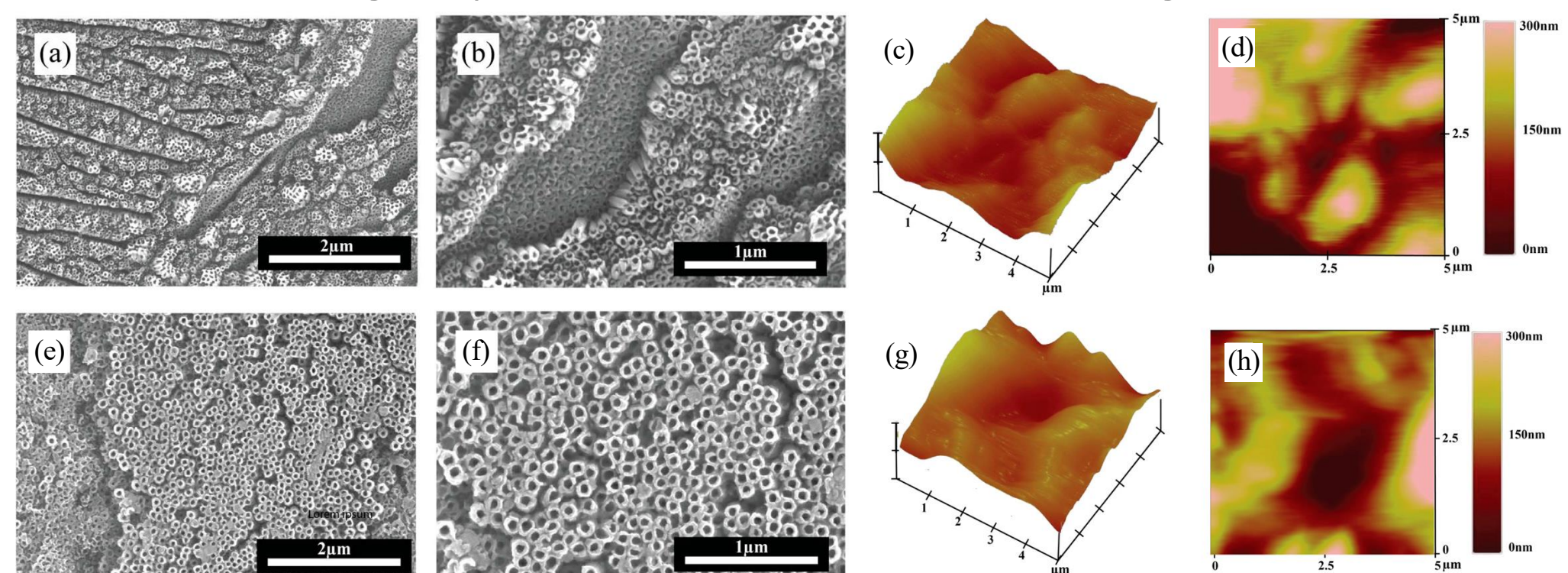
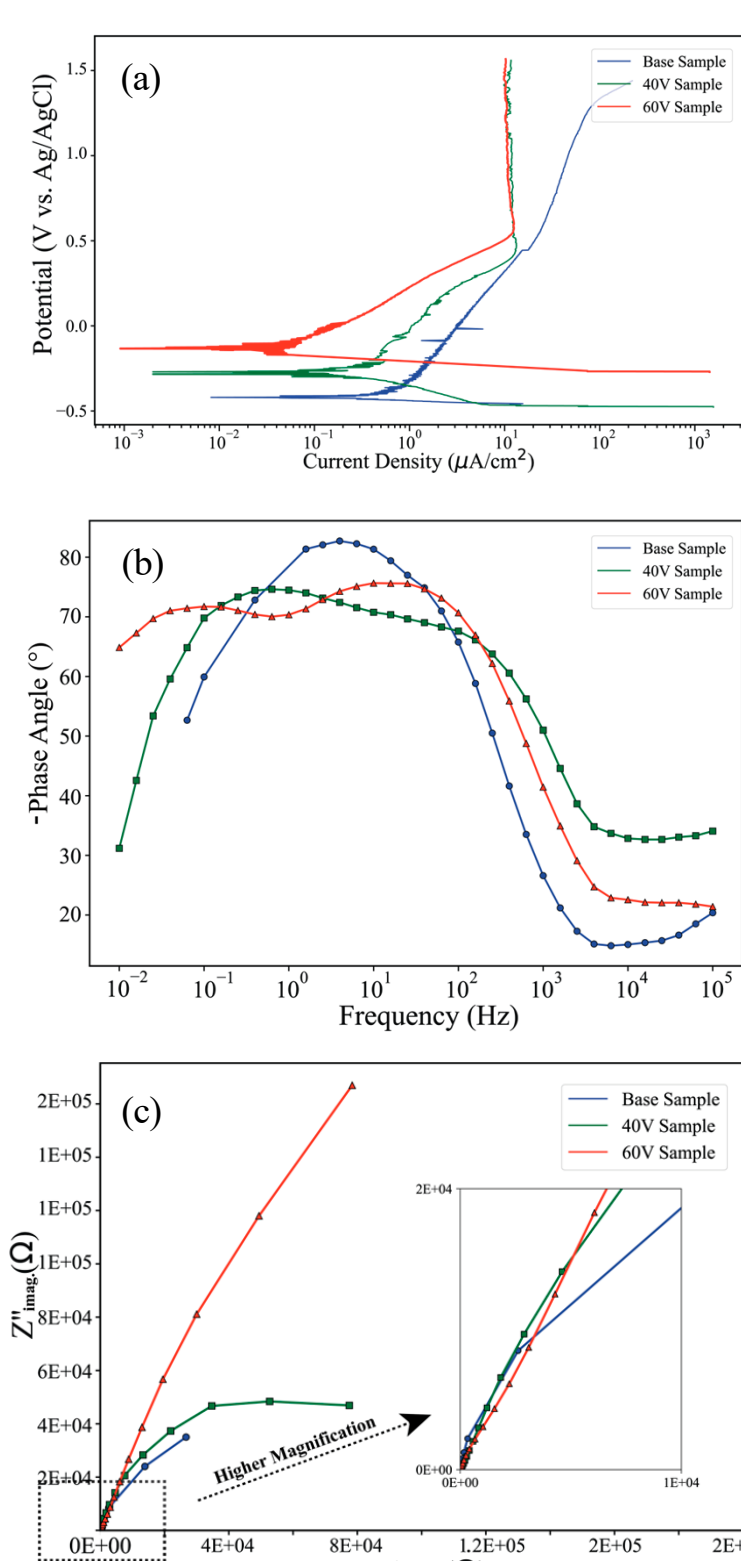


Figure 3. SEM images of TiO₂ nanotube formation and Topographic AFM images (3D, 2D) of the Ti64 samples at 40V (a, b, c, d) and 60V (e, f, g, h)



The electrochemical impedance spectra (Nyquist and Bode plots) indicate a clear enhancement in corrosion resistance after anodization. In the Nyquist plot, both anodized samples show capacitive semicircles, highlighting effective barrier behaviour against electrolyte penetration. The 60V coating displays the largest semicircle diameter, followed by the 40V sample, while the base Ti64 exhibits the smallest loop, confirming its lower corrosion resistance. The presence of two capacitive loops on the anodized surfaces suggests two distinct time constants due to the oxide layer and the electrolyte interface. In the Bode-phase diagram, the 60V sample shows a broader and higher-phase-angle plateau, indicating improved dielectric properties and the formation of a denser, more protective oxide film.

CONCLUSION

Anodization of EB-PBF Ti-6Al-4V successfully produced TiO₂ nanotube coatings with voltage-dependent properties. The 40 V samples produced uniform nanotubes with higher hardness, while the 60 V samples produced thicker, less-ordered nanotubes with superior corrosion resistance. Both anodized surfaces exhibited improved mechanical, electrochemical, and bioactive performance compared to the base alloy, confirming anodization as an effective post-processing method for enhancing the performance of EB-PBF Ti64 implants.