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Abstract

Advanced Hip Implants: Combining a novel metastable b-Ti alloy and lattice structures to reduce stress shielding

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Total Hip Replacement is a widely performed and highly effective procedure for restoring hip function in patients with degenerative joint conditions. However, stress shielding remains a major challenge, as the stiffness mismatch between the bone and the implant may cause bone resorption and implant instability. This may potentially lead to the need for revision surgeries. This study explores a combined strategy to address this issue by integrating Ti21S, a promising novel metastable β-titanium alloy for biomedical applications with a lower elastic modulus than conventional Ti6Al4V, and lattice structures. The goal is to ensure stiffness compatibility and promote osteointegration. Two prosthetic designs were investigated: the first incorporates TPMS (Triply Periodic Minimal Surface) and auxetic lattice structures, while the second relies solely on TPMS, both with varying relative densities to optimize load distribution. TPMS structures are particularly advantageous for orthopedic devices due to their high surface area and interconnected porosity. Their zero-mean curvature and mechanical properties closely mimic those of trabecular bone, promoting osteointegration and reducing stiffness mismatch. Furthermore, the integration of auxetic structures in a specific implant region subjected to compressive loading is designed to leverage the negative Poisson's ratio. This promotes continuous bone adhesion and mechanical stimulation. Mechanical performance was assessed through fatigue and quasi-static compression tests, while Digital Image Correlation (DIC) was used to analyze surface deformation. Microstructural analysis identified potential manufacturing defects, and Finite Element Method (FEM) simulations, simplified via homogenization, were conducted to validate experimental findings. The elastic modulus of the AUX-TPMS prosthesis is 1.4501 kN/mm and that of the TPMS prosthesis is 1.2623 kN/mm. These values are similar to Ti6Al4V porous hip stems (0.42–2.18 kN/mm) and close to the typical human femur stiffness (1.446 kN/mm for males and 1.163 kN/mm for females). The fatigue resistance was lower, with the AUX-TPMS lasting 40000 cycles and the TPMS 83491 cycles. This can be attributed to printing defects (porosity, partially melted powder on the surface, and surface roughness), the absence of heat treatments, and the application of testing standards designed for bulk implants rather than lattice-based structures. While the TPMS prosthesis offers better stiffness and fatigue resistance, the AUX-TPMS design allows lateral expansion, improving bone regeneration by preventing detachment on one side. This study demonstrates the potential of combining metastable β-titanium alloy and mechanical metamaterials for next-generation orthopedic implants that reduce stress shielding, bone resorption, and revision surgeries.

AUTHOR'S STATEMENT

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