Development and evaluation of 3D-printed gyroid beta-titanium implants for osteoporotic bone

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Introduction

Osteoporotic bone critically challenges the long-term stability of titanium implants, whereas porous gyroid surface structures produced by SLM may enhance mechanical interlocking and osseointegration. In this project, we develop gyroid structures from conventional Ti6Al4V and an experimental β-titanium alloy Ti25Nb4Ta8Sn and optimise 3D-printing parameters for thin-walled geometries close to the technological limit, including chemical surface etching to remove loosely bonded powder particles and to adjust the internal wall architecture. The aim is to obtain geometrically reproducible implant-like samples with controlled porosity and a defined degree of etching as a basis for subsequent in vitro and in vivo evaluation in an osteoporotic model. In the first in vivo phase, gyroid implants made of Ti6Al4V will be tested, followed by a second phase with gyroid implants manufactured from the β-titanium alloy Ti25Nb4Ta8Sn.

Ti25Nb4Ta8Sn gyroid surface

Gyroid structures made of β-titanium alloy Ti25Nb4Ta8Sn are used as a surface layer on cylindrical implant-like samples intended for in vivo insertion into osteoporotic bone; the surface porosity is defined by three target pore size variants (pore size 300 µm, 600 µm, and 900 µm where "pore size" corresponds to the nominal spacing and curvature of the elementary gyroid cell in the CAD model (i.e. the distance between opposite surface nodes of the gyroid) (Fig1), and these three levels represent progressively fine, medium-open, and highly open architectures, allowing us to adjust the bone–implant contact area, permeability for cells and fluids, and the local stiffness of the gyroid layer.

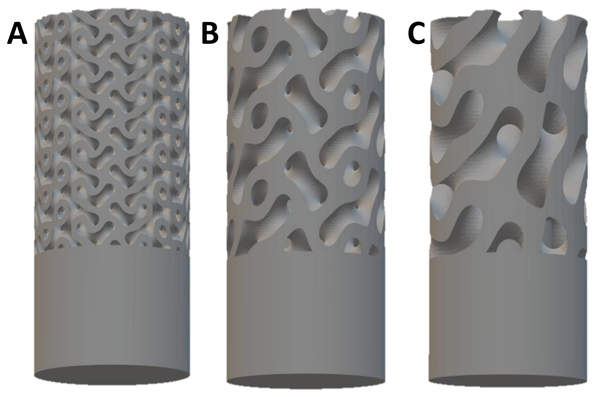


Fig. 1: Parametric models of the gyroid surface structure used as templates for the fabrication of implant carriers with nominal pore sizes of A: 300, B: 600, and C: 900.

Surface etching of Ti alloys

Chemical etching was used as a targeted post-processing step to remove loosely bonded powder particles from the internal surfaces of the gyroid structures and to achieve controlled wall thinning prior to in vivo implantation. Cylindrical specimens made of β-titanium alloy Ti25Nb4Ta8Sn were etched in a two-step protocol in an ultrasonic bath (Grant XB2): 3 minutes in solution A (deionised water : HNO_3 : HF 5:1:1 with oxalic acid 8.5 $mg \cdot mL^{-1}$) and 3 minutes in solution B (deionised water : HNO_3 : HCl : HF 13:5:5:1), followed by 10 minutes of ultrasonic cleaning in deionised water. For Ti6Al4V, a solution of deionised water : HNO_3 : HF (78:20:2 by volume) was used with an etching time of 6 minutes and the same final ultrasonic rinse. SEM images show that etching effectively removed the dense layer of adhered powder from the gyroid walls and transformed the initially highly granular surface into a smoother, more compact and layered morphology (Fig. 2).

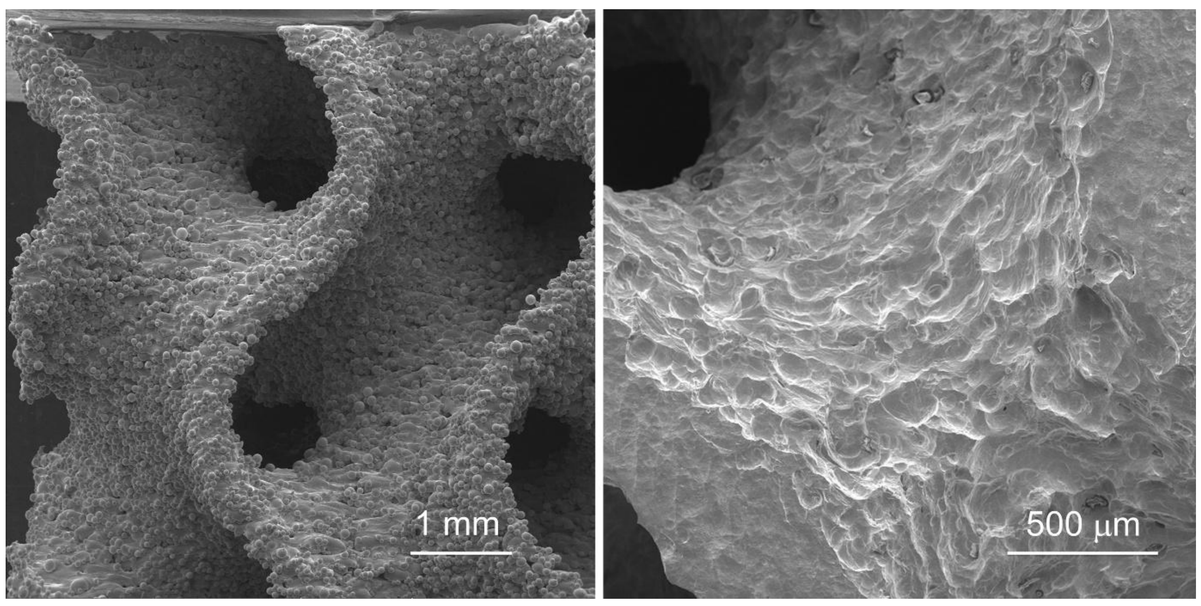


Fig. 2: SEM images of the β-titanium Ti25Nb4Ta8Sn gyroid surface before etching, showing a dense layer of adhered powder particles on the gyroid walls (left), and after chemical etching, revealing a smoother, more compact and layered surface morphology with removed loosely bonded particles (right).

In-vitro

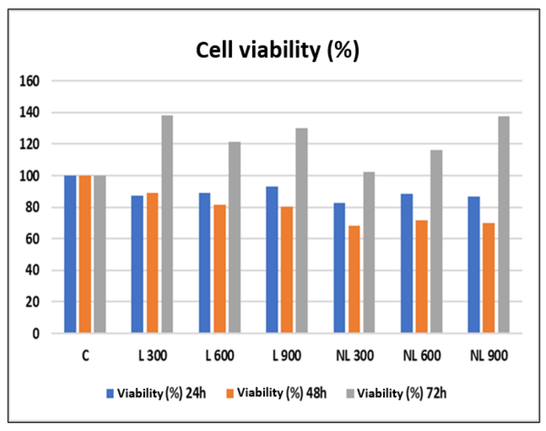


Fig. 3. Cell viability of MG-63 cells on control (C), etched (L) and non-etched (NL) gyroid structures with different pore sizes (300, 600 and 900 µm) after 24, 48 and 72 h of cultivation, expressed as percentage of the control.

Gyroid structures made of Ti6Al4V with a diameter of 13 mm and a height of 2 mm, manufactured with three pore sizes (300, 600 and 900 µm) in etched and non-etched variants, were used for in vitro evaluation of the cellular response of osteoblast-like MG-63 cells. Samples were seeded with cells and their metabolic activity was quantified using the MTT assay after 24, 48 and 72 hours of cultivation (Fig. 3), while cell morphology and colonisation of the porous structure were assessed by SEM after 7 and 14 days of cultivation (Fig. 4).

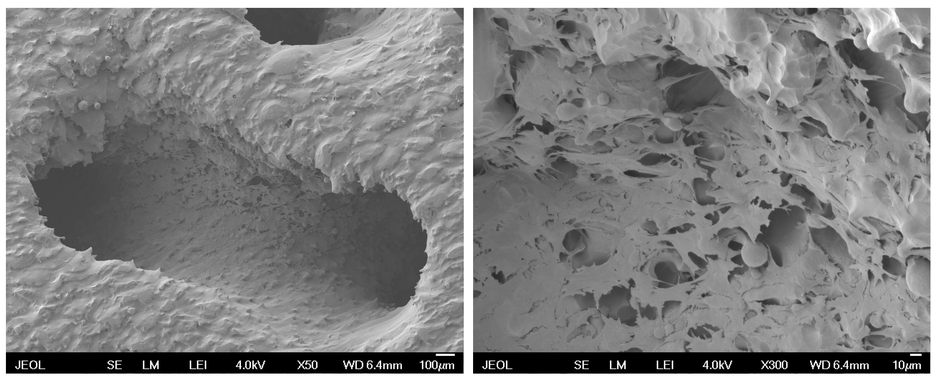


Fig. 4: SEM images of non-etched gyroid structures with pore size 900 µm after 7 days of MG-63 cell cultivation, showing cell coverage of the pore surfaces at lower (left) and higher (right) magnification..

In-vivo

In our project, minipigs with a pharmacologically induced osteopenic to osteoporotic condition are used as a large-animal model for testing gyroid implants. The osteoporosis-like state is induced by a specialised diet with reduced calcium and phosphorus content, supplemented with prednisone administered according to the animal's body weight (1 mg/kg body weight per day for the first 2 months, followed by 0.5 mg/kg per day) up to the time of implantation. The effect of this regimen is monitored repeatedly over time using haematological and biochemical markers, which in pilot and follow-up experiments showed typical changes (e.g. increased albumin, cholesterol and calcium and decreased total ALP) with partial normalisation after the wash-out phase, confirming the suitability of the protocol for establishing an osteoporotic minipig model.

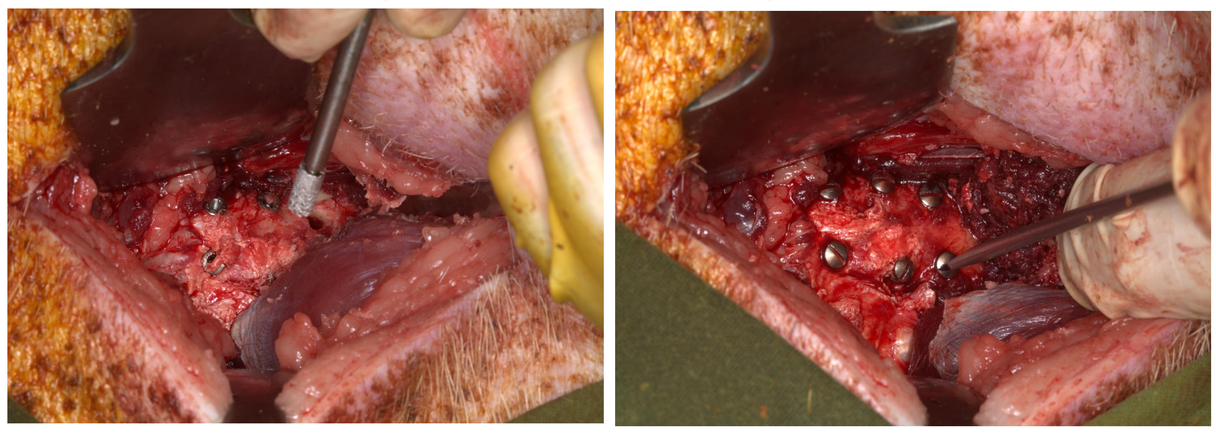


Fig. 5: Intraoperative view of cylindrical test implants being inserted into prepared femoral defects of the minipig (left) and final configuration of multiple implanted samples fixed in the distal femur (right).

Conclusions

For both materials (Ti6Al4V, Ti25Nb4Ta8Sn) and all selected pore sizes, we will evaluate the mechanical, morphological and biological behaviour of the structures:

- Mechanical testing of 3D-printed specimens (tension, bending, fatigue). In vitro assays with MG-63 cells (MTT, SEM) to assess viability, morphology and ingrowth into etched and non-etched structures.
- Micro-CT analysis of defects, geometric accuracy, and the effect of etching and tissue ingrowth on pore architecture.
- Mechanical tests (tension, bending, fatigue, fibula fracture).
- Histological sections of peri-implant bone for detailed evaluation of osteointegration.

Acknowledgments

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