

Fatigue and Joining Properties of a Bioinspired Orthopaedic Biomaterial with Adjustable Mechanical Properties Based on Sintered Titanium Fibers

Olaf Andersen¹, Ulrike Jehring¹, Christian Redlich¹, Cris Kostmann¹, Georg Pöhle¹, Matthias Rüger^{2,3}, Thomas Weißgärber⁴
¹Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM, Germany, ²University Children's Hospital, UZH, Switzerland,
³ETH Zurich, Switzerland, ⁴Institute of Materials Science, Chair Powder Metallurgy, Technical University of Dresden, Germany
 olaf.andersen@ifam-dd.fraunhofer.de

Disclosures: Olaf Andersen (N), Ulrike Jehring (N), Christian Redlich (N), Cris Kostmann (N), Georg Pöhle (N), Matthias Rüger (N), Thomas Weißgärber (N)

INTRODUCTION: Inadequate mechanical compliance of orthopaedic implants can result in excessive strain of the biologic interface and ultimately, aseptic loosening. To compound this issue, the elastic modulus of human trabecular bone within a distinct skeletal region such as the proximal femur can vary by as much as 200 % between the trochanteric region and femoral head. Considering these significant interindividual variations in bone density and changes in remodelling capacity over time, a biomimetic orthopaedic material designed for load bearing bone should be (i) available in mechanical strengths and stiffnesses most suitable to the peri-implant bone tissue of a specific patient, (ii) allow for continuous remodelling processes within and around the implant to comply with biological changes at the host site and (iii) provide a large surface area for improved bone-implant interaction in applications with comparably small bone mass like ankle joint or shoulder endoprotheses. We hypothesized that a fiber-based biometal with adjustable anisotropic mechanical properties could facilitate continuous remodelling and improve long-term implant survival. A material comprised of strategically layered, sintered titanium fibers with anisotropic mechanical properties adjustable in three dimensions (TiFi) was therefore developed (Figs. 1, 2). TiFi showed already compressive yield strengths of up to 50 MPa and anisotropical mechanical properties according to fiber layout. Additionally, TiFi demonstrated excellent osteoconductivity and in vitro biocompatibility in sheep metaphyseal trepanation model. Current investigations focus on fatigue properties and joining methods in order to combine TiFi with massive implant structures as required i. e. for ankle joint and shoulder endoprotheses.

METHODS: The TiFi matrix material is an unalloyed titanium. It is made from titanium fiber fleeces consisting of individual fibers (approx. 36 ± 10 tex) that can be stacked in parallel and cross-ply topologies in different ratios. In this study, an additional needling operation was applied to the fiber fleeces before stacking. After stacking, the fibers are bonded together by a sintering step. Sintering is carried out in high vacuum at temperatures of 1320 °C for 160 min. The desired thickness and total porosity of the structure (between 70 and 75 %) is achieved by applying an appropriate weight on top of the stack, while space holders prevent the stack from compressing farther than desired. Thus, a good inter-fiber contact and well-developed sinter bonds are achieved. If needed, the semi-finished sintered material can be shaped by milling, this way being able to provide net-shape true 3D geometries that are oriented in the mechanically most favorable direction. Fatigue test samples were prepared from the sintered fiber structures by water jet cutting. Fatigue testing was carried out in SBF at 37 °C for up to 10^7 cycles, following the procedure described in DIN 50100:2016 "Fatigue testing - Performance and evaluation of cyclic tests with constant load amplitude for metallic material specimens and components". The applied testing frequency was 1.7 Hz. For the assessment of the joining of TiFi to massive implant structures, shear-tensile test samples were prepared by sinter-bonding of already sintered TiFi fiber structures to titanium sheets. Testing was carried out in accordance with DIN EN 1465:2009 "Shear tensile test at room temperature".

RESULTS: TiFi demonstrated mean fatigue strength values around 11 MPa. The mean tensile shear strength amounted to 2.31 MPa with a low standard deviation of 0.15 MPa.

DISCUSSION: The fatigue strength compares favorably with the very scarce fatigue data available for 3D printed porous implant materials, with the total porosity being the dominating parameter. Further testing is on the way, applying a stair-step procedure in order to obtain statistically valid data. The shear tensile tests of the sinter-bonded samples showed surprisingly high values and exclusively failure within the fiber structure and not at the bonding site which is a desired outcome (Fig. 3).

SIGNIFICANCE/CLINICAL RELEVANCE: The biometal analyzed in this study demonstrated anisotropic mechanical properties similar to natural bone, excellent osteoconductivity, very good fatigue strength properties and consequently, feasibility as an orthopaedic implant material. It was further demonstrated that sinter bonding is a reasonable method of joining TiFi to massive metallic implant structures made from titanium materials.

IMAGES AND TABLES:



Figure 1. A cuboid sample (10x10x10mm³) of sintered titanium fibers (TiFi).

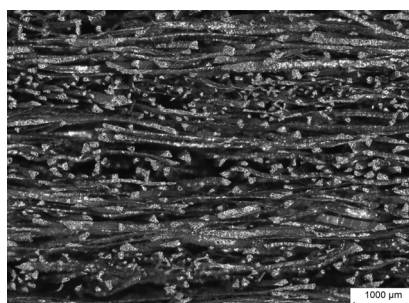


Figure 2. Metallographic cross section of sintered titanium fibers (TiFi).

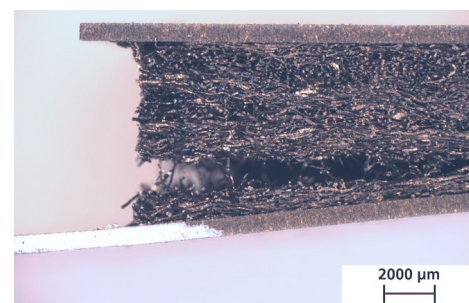


Figure 3. Tensile shear test sample after failure. Rupture occurs well within the fiber structure and not at the interface between the fibers and the titanium sheet.