NATURE-INSPIRED TOUGHENING MECHANISM OF 3D PRINTED HYDROXYAPATITE SCAFFOLDS FOR BONE TISSUE ENGINEERING

Luca D'Andrea (1), Ting Yang (2), Ming Dao (2), Pasquale Vena (1)

1. Politecnico di Milano, Italy; 2. Massachusetts Institute of Technology, USA.

Introduction

The mechanical performances of Triply Periodic Minimal Surfaces (TPMS) have been extensively studied for Bone Tissue Engineering (BTE) applications [1]. Despite its biocompatibility and bioactivity, hydroxyapatite (HAP) usage in BTE applications is limited by its intrinsic brittleness. Furthermore, the strength and the toughness decrease drastically when porous structures (i.e. BTE scaffolds) are involved. Starfish ossicles exhibit a mineralized TPMS structure at a micron scale. The presence of dislocation-like defects in these structures makes the structure tougher [2]. 3D printing techniques can produce porous ceramic scaffolds with high fidelity. Finite Element Modeling (FEM) has been employed to assess both the elastic and fracture behavior of ceramic scaffolds [3]. The aim of this work is to determine the mechanical performances of a Schwartz-P TPMS and assess the role of an edge dislocation in the crack pattern evolution using a combined approach of FEM and experimental tests.

Materials and Methods

Bulk miniaturized HAP samples have 3D printed through vat-photopolymerization to assess the mechanical parameters to be used in FEM [4]. Morphological and mechanical characterization has been performed by means of synchrotron light radiation Computed micro-Tomography (µCT), micro-bendings and nanoindentations. The Schwartz-P TPMS have been designed in Matlab by using the following function:

$$f = \cos\left(\frac{2\pi x c_y}{n}\right) + \cos\left(\frac{2\pi y c_x}{n}\right) + \cos\left(\frac{2\pi z c_z}{n}\right) - b$$

where x, y and z represent the Cartesian coordinates, b the known term, n the number of voxels used for the spatial discretization and c_x, c_y, and c_z the number of repetitive units in the space. The variable c_y has been properly tailored to provide a smooth transition between two adjacent integer values. Displacement-controlled elastic compressions have been performed in ABAQUS/Standard to assess the effective stiffness of the scaffold. The structure has been rotated from 0° to 90° with a step of 5° to assess the role of the angle between the load and the dislocation. Selected configurations, namely 0°, 45° and 90°, have been tested in compression to assess the fracture behavior by using ABAQUS/Explicit. The maximum principal stress criterion has been used for element deletion.

Results

µCT scans reveal an intrinsic porosity of 0.3% in the bulk samples. Micro bendings and nanoindentation restitute a stiffness of 100 GPa and a flexural strength of 100 MPa. The maximum effective stiffness of the TPMS is 22 GPa, corresponding to the 0° and 90° configuration, whereas the 45° configuration is the more compliant (15 GPa). The fracture behavior of the 0° dislocation configuration (Figure 1) exhibits the lower strength, while the higher is represented by the ideal structure in 0° and 90° configuration.

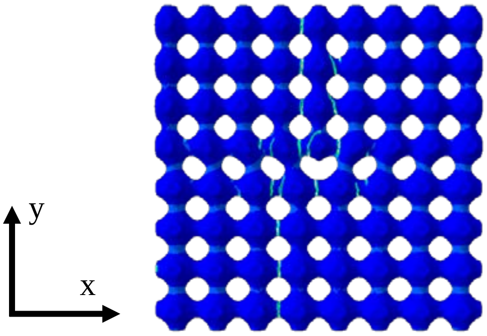

Figure 1: fracture pattern (in green) under compressive load (y direction). The crack starts at the dislocation tip and propagates vertically to the two extremities.

Discussion

The dimensions of the voids of intrinsic porosity can be represented as a bimodal distribution, where the largest pores are concentrated in the core of the beam. Due to the low value of intrinsic porosity, 3D printed HAP can be modeled as a continuum material in FEM. Concerning the TPMS, the effective stiffness in the 0° and 90° configuration is in accordance with a polynomial fitting of 3D printed porous scaffolds [5]. In each load condition, the presence of the dislocation does not affect the effective stiffness of the structure. Even if the ideal structure exhibits the highest strength, the failure is catastrophically brittle, whereas the 90° dislocation configuration is tougher since the dislocation introduces a local increase of stress at the tip of the dislocation, preserving other areas with load-bearing capability. Further fracture simulations are ongoing to corroborate the current results and a robust experimental campaign to validate the numerical results will be performed.

References

1. Khaleghi et al, *Materials and Design*, 210, 2021.
2. Yang et al, *Science*, 375, 647-652, 2022.
3. Miranda et al, *JMBBM*, 646-655, 83(3), 2007.
4. Baino et al, *J. of the American Ceramic Society*, 2022
5. D'Andrea et al, *Materials*, 15, 6344, 2022.

Acknowledgments

The authors kindly acknowledge the "Progetto Roberto Rocca" for contributing to funding this project.