# *STRAIN ACCUMULATION OF POROUS TITANIUM ALLOYS REVEALED BY IN-SITU X-RAY TOMOGRAPHY AND DIGITAL VOLUME CORRELATION*

Shao-gang Wang[*1], L. Zhang[*1]

[1]Shenyang National Laboratory for Materials Science, Institute of Metal Research,

Chinese Academy of Sciences, Shenyang 110016, China

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**Summary:** The evolution of 3D displacement fields and the deformation mechanism as well as the distribution, the shape, the size and the porosity of internal defects were successfully acquired by in-situ X-ray tomography and digital volume correlation techniques. These techniques could further guide the development and optimization of new advanced materials with 3D topological microstructures.

## 1. INTRODUCTION

Additive manufacturing (AM), an emerging revolutionary manufacturing technique, has been attracting great attention all over the world. Among different AM methods, Selective Laser Melting (SLM) and Electron Beam Melting (EBM) can satisfy the increasing demands of aerospace and biomedical fields with the advantages of not only producing prototypes or products rapidly and cost-effectively, but also providing accurate control over both internal architectures and complex-shapes. Titanium alloys, as one kind of potential bio-implant materials, have been fabricated using both the EBM and SLM techniques, and their mechanical properties have been reported to be closely related to the processing parameters, part orientation, surface finish and post heat treatment. However, the topological microstructure of AM titanium alloys usually characterized using optical microscope and scanning electron microscope from 2D view. Such 2D information cannot tell us topological features and what happened beneath the surface, and may give misleading to the correlation between the microstructure and mechanical properties of AM titanium alloys.

In this talk, we aimed to present some laws among internal defects such as pores, static mechanical properties, cyclic properties, and deformation and fracture mechanisms of AM titanium alloys with different topological designs form 3D view. **For uniform microstructural architectures**, the relationships between 3D defects and mechanical properties such as compression, tensile and fatigue properties of the samples prepared by EBM and SLM were focused. Full dense Ti–6Al–4V and porous biomedical Ti-24Nb-4Zr-8Sn (abbreviated as Ti2448) alloys were compared using X-ray tomography (XRT) technique to discuss the influence of the change of microstructural architectures. Some unique 3D characteristics were observed. To further understand the relationship between 3D pores and mechanical properties of uniform porous Ti2448, the scan speed of heating source beams was tuned to change the porosity and the struts, and the influence on the stress response was also discussed. **For non-uniform microstructural architectures**, several functionally graded meshes composed of three unit cells were designed. The actual diameters and porosities of scaffold struts for three kinds of unit cells were measured by using XRT. The deformation features of different graded meshes were revealed by in situ XRT, and the evolvement of the 3D strain maps were visualized by digital volume correlation (DVC) technique. According to these knowledge obtained from in-situ XRT and DVC, how to optimize the overall properties of porous AM titanium alloys were discussed.

## 2. EXPERIMENTAL METHOD

The samples of AM titanium alloys with different topological microstructural architectures fabricated by the EBM and SLM techniques were scanned using Xradia VersaXRM-500 X-ray tomography system with an accelerating voltage of 120 kV. In order to study internal defects, the deformation and fracture mechanism, two types of in situ XRT tests were designed. One was ex-situ XRT test, in which several XRT scans were made on the same sample after certain stages of fatigue tests. The second was interrupted in situ XRT test, in which an in-situ Deben micro-test compression stage was used, and the same sample was scanned several times, once the in situ compression test was interrupted. For each scan, a total of 1601 projections was recorded when the sample was rotated about 360°, and then the resultant structural feature was reconstructed by filtered back projection

*e-mail: wangshaogang@imr.ac.cn

algorithm using XMRconstructor. The 3D data was then analyzed by Avizo fire software. The pixel size varies from 1.9 to 13.5 μm.

Digital volume correlation method can evaluate full-field mechanical response on the base of the XRT technique, and is able to calculate complete 3D displacement and strain map. Here, DVC codes running on Davis platform offered by LaVision (www.lavision.de) were used to measure the displacement vector field throughout the sample by importing the volume images of samples in unloaded and loaded state acquired from XRT. The visualization of the displacement vector field was achieved using the open-source software ParaView.

## 3. RESULTS

1) **<u>For uniform microstructural architectures</u>**,

- For fully dense EBM and SLM Ti–6Al–4V samples, we found an intriguing phenomenon that large pores generally occurred on the edge of the EBM samples whereas they gathered in a form of vertical walls which were intersected each other in orthogonal direction for SLM samples. Contrary to the tensile properties of SLM and EBM samples, it seems that fatigue strength was greatly affected by these pores. The fatigue limits of both SLM and EBM samples could be significantly enhanced by closing of the pores using hot iso-static pressing (HIP) technique **[1]**.
- For porous Ti2448 alloy produced by EBM and SLM, the number of defects in the SLM samples was about 10 times that of EBM samples. The defects in as-fabricated EBM samples were in a spherical shape while those in SLM samples showed a conical-like shape. These defects mainly influence fatigue life at higher stresses level rather than fatigue strength at lower stress level and the static properties **[2]**.
- For porous Ti2448 alloy produced by EBM, the scan speed of electron beam greatly affect the size and number of defects. In comparison with defects, the strut seems to be a more important factor for the mechanical performance **[3]**.

2) **<u>For non-uniform microstructural architectures</u>**,

There are no significant differences in the distribution and characteristics of pores for all the three kinds of unit cells. Two kinds of in situ XRT experiments combined with digital volume correlation technique revealed stress redistribution and the progressive initiation of the cracks in the constituent meshes during static compression and cyclic compressive fatigue tests. This internal information gave new insights into how the substructure of graded meshes deformed and the crack nucleated in microscale while the entire sample was under elastic deformation in macroscale, and could deepen the understanding of the relationship between topological designs of graded structure and different properties **[4]**.

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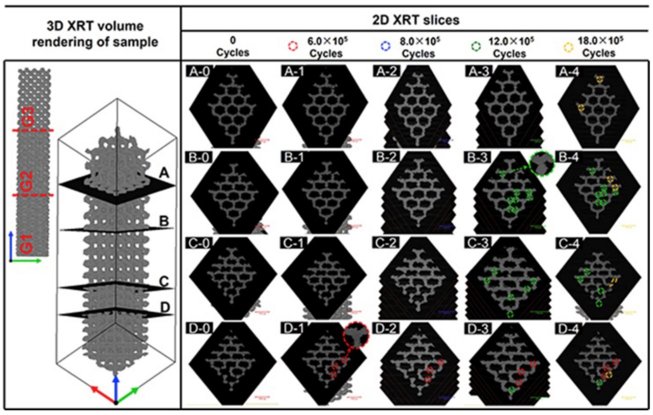


**Figure 1** In-situ XRT results of the graded meshes after being stopped at different stages of cyclic loading. The colored dash cycles indicate the cracks detected in the mesh struts after a certain number of cycles. **[4]**