Strain Characterization and Modeling of Bone-Implant System

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Statement of Purpose: Bone is a composite material whose complex hierarchical structure contributes to its unique mechanical properties: stiff and tough but lightweight. However, when bone is broken or severely damaged, repair is necessary to restore its function and properties. One repair method is use of bone implants. The introduction of a bone implant into the natural bone influences the internal micro-/nano-scale stress/strain distribution, which eventually impacts the bone repair process. Therefore, in this article, we introduce a method to characterize the nanoscale strain distribution in both bone (organic/inorganic phases respectively) and bone implant. We also use the finite element method to simulate the evolution of the corresponding strain distribution in the bone-implant system to provide insight for further design of bone implant.

Methods: The bone used in the experiment was bovine femurs and cut into a rectangular cuboid by a low-speed diamond wafering blade. Cp-2 Titanium implants (about 43% porosity) were customized into rod-like shapes with a 5 mm height by 3mm diameter with a threaded internal hole on the top. To drive the implant into the bone, a hole was drilled in the bone sample and a cp-2 solid Titanium screw-head with matching threads was also used. This process was done very carefully to minimize the damage to the bone-implant system. The geometry sketch of the bone-implant system is shown in Figure. 1.

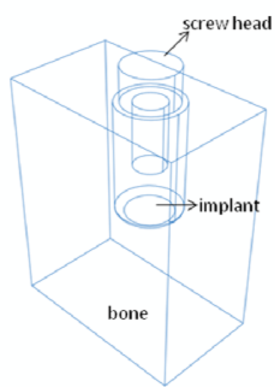

Figure 1. Geometry Sketch of Bone-Implant System

All the mechanical tests were carried out at Advanced Photon Source, Argonne National Laboratory. The bone-implant system was loaded in uniaxial compression with a ten-step load-unload pattern. At every load hold, X-ray diffraction measurements were performed on a 7 by 8 point grid. Wide angle X-ray scattering measurement showed the lattice strain information in mineral and Titanium phases while small angle X-ray scattering measurement showed the combined strain of mineral and collagen phases.

The simulation was implemented by finite element method (software Abaqus). The geometrical and loading set-up in the model reproduced the experimental conditions. The bone and porous Titanium implant were assigned with elastic-plastic properties while the solid Titanium screw-head was only considered as elastic. The composite strain obtained from simulation was compared with small angle X-ray diffraction data. By using our previously established nanoscale strain model of bone [1], we deduced the lattice strain from the composite strain and compared it with wide angle X-ray scattering data.

Results: Both small angle and wide angle X-ray scattering data were analyzed [2] to create 7×8 point strain maps. Figure 2 shows an example of small angle X-ray scattering strain map at the maximal load condition. From the series of strain maps, the evolution of strain distribution during load-unload process was illustrated, and the stress transfer information between different phases and materials was obtained.

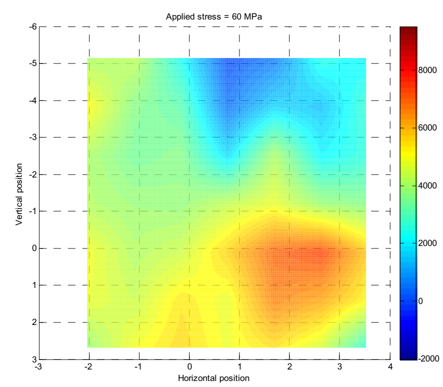

Figure 2. Small Angle X-Ray Scattering Strain at the Maximal Load Condition

The finite element method simulation also provided a series of strain maps -- composite strains corresponding to small angle X-ray scattering data and nanoscale strains corresponding to wide angle X-ray scattering data.

Conclusions: The micro-/nano-scale strain distribution within different phases and different materials was obtained by X-ray diffraction technique in a macroscopic scale level. The strain evolution and load transfer information were illustrated by both experimental data and finite element simulation. The interactions on the interfaces between bone-porous Titanium implant and porous Titanium implant-solid Titanium screw head were discussed in the model. The simulation results were in good agreement with experimental measurement.

References: [1] Yuan F. Biomech. Model. Mechanobiol. in press. doi:10.1007/s10237-010-0223-9.
[2] Almer JD. J. Struct. Biol. 2005;152:14-27.