X-ray micro-tomography applied to NASA's materials research: heat shields, parachutes and asteroids

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Summary: X-ray micro-tomography is used to support the research on materials carried out at NASA Ames Research Center. The technique is applied to a variety of applications, including the ability to characterize heat shield materials for planetary entry, to study the Earth- impacting asteroids, and to improve broadcloths of spacecraft parachutes. From micro-tomography images, relevant morphological and transport properties are determined and validated against experimental data.

1. Introduction

In building spacecraft, satellites, space suits or any other system to explore our Universe, NASA adopts advanced materials with tailored properties that allow handling the extreme environmental conditions of outer space. As the properties and performance of these materials are determined by their 3D microstructure, imaging materials in 3D, at the scale of their constituents, is an important part of their characterization, design and analysis. X-ray micro-tomography (micro-CT) is an established technique to non-destructively characterize material structures at scales varying from the sub-micron to the centimeter. Synchrotron sources of x-rays allow to apply the technique to a large variety of materials and enable the use of environmental cells where the materials can be subjected to actual operational conditions, such as thermal and mechanical loads or reactive atmospheres.
In this paper, we illustrate three applications of x-ray micro-CT to research on advanced materials of interest to NASA. The first application is the study of high temperature fibrous media, used in low-density thermal protection systems (TPS) for atmospheric entry vehicles. Critical to this class of materials is the ability to model with high-fidelity the physical processes occurring in their porous structure, such as heat transfer, chemical phenomena and flow transport. Secondly, micro-CT is applied to characterize textiles of parachute used for slowing down spacecraft during atmospheric descent. From the 3D images fabric permeability is computed. The third application concerns the analysis of meteoritic materials. In an effort of utilizing NASA's design tools for entry spacecraft to predict energies and dynamics of Earth impacting asteroids, imaging of meteorites helps understanding their microstructure and their fracture and break-up upon atmospheric impact.

2. Methods

Experiments were performed at the beamline 8.3.2 of the Advanced Light Source (ALS) synchrotron facility at Lawrence Berkeley National Laboratory. The capabilities of the facility are described with detail in [1]. For this work, we used x-ray energies between 15 and 18 keV to image low-density fibrous materials and white light for metal-rich, dense meteorites. Using a 2560×2160 pixels detector and an Optique Peter microscope, a pixel size of ~0.65 µm was obtained with a 10× magnification lens in order to resolve fibrous structures. A 5× magnification, providing a pixel size of ~1.3 µm, was instead used for imaging meteorite materials. During the scans a total of 1024 radiographs were acquired and reconstructed using the TomoPy software. The Avizo package was used for segmentation and visualization, while material properties and simulations were performed using software described in [2-

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3], as well as the Porous Material Analysis (PuMA) code, presented in a companion paper.

3. Results

Micro-tomography images of the different materials investigated are shown in Fig. 1. Morphological information at the microscale can be characterized for both fibrous and dense materials. Fig. 1(a) shows temperature and velocity fields within 85-90% porous carbon fiber material. Heat transfer is simulated using a finite difference method that allows the effective material conductivity to be computed from the conductivity of the constituting phases [2]. The computations show that, due to the high porosity, different conductivities of the gas phase can result in up to 20% differences in the effective material conductivity [2]. The flow-field is computed using the Direct Simulation Monte Carlo (DSMC) method, which accounts for slip effects occurring in porous heat shield material operating at high temperature and low pressures. It is shown that the DSMC method applied to micro-CT is able to predict the Klinkenberg permeability of the material at high temperature. Simulations at temperature between ambient and 1500 K show an excellent agreement when compared with laboratory measurements in a high temperature flow-tube setup [3].

Porosity and permeability are also computed based on high-resolution tomography of the nylon ripstop weave of a supersonic parachute, shown in Fig. 1(b). Values are to be compared for relaxed fabrics and weaves under biaxial tension that simulates an actual operational load for the deployed parachute.

The micro-CT of the Tamdakht H5 Chondrite Meteorite (Fig. 1(c)) reveals a heterogeneous micro-structure composed of a porous glassy crust, high-density Fe- and Ni-rich grains, and olivine and peroxine grains immersed in a lower density matrix with a large concentration of micron-size fractures. The propagation of those fractures is to be studied in in-situ experiments where the meteorite material is subjected to compression loads until failure.

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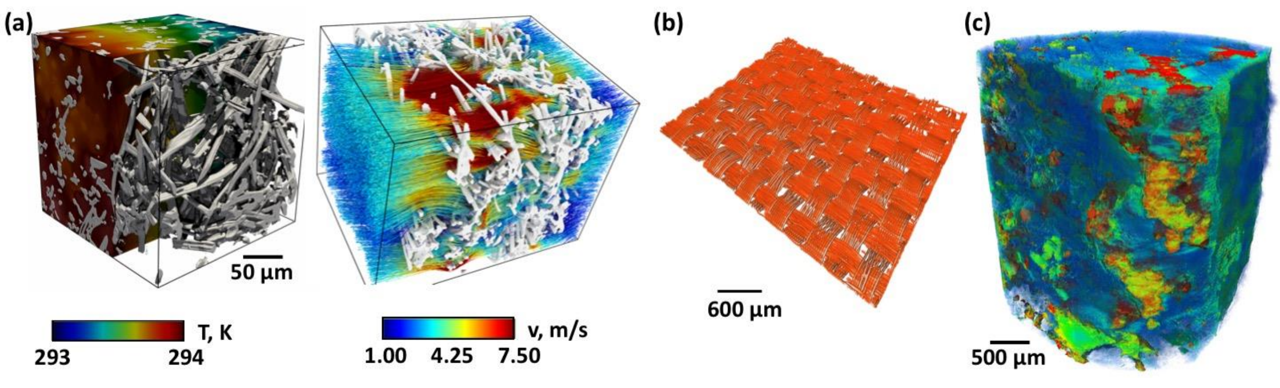

Figure 1: (a) Temperature (left) and velocity (right) fields in a porous carbon fiber insulator. (b) Micro-tomography of a parachute fabric. (c) Micro-tomography of the Tamdakht meteorite. The color map shows areas of different density within the material (red is denser).