X-ray microtomography applied to NASA missions and projects

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Ablative Thermal Protection Systems

Carbon preform + Resin = PICA

Stackpoole et al., AIAA 2008-1202
www.spacex.com
Stardust Capsule
Dragon V1 & V2
Mars Science Laboratory
Material Design and Modeling

Bow Shock

Boundary Layer

Char Layer

Pyrolysis Zone

Virgin Material

Substructure

Lachaud and Mansour, JHT 2013

Lawson et al. 2010
X-ray micro-tomography

- Advanced Light Source (ALS) at the Lawrence Berkeley Natl. Laboratory
- Synchrotron electron accelerator used to produce 14Kev X-rays
- Used for many research areas, including optics, chemical reaction dynamics, biological imaging, and **X-ray micro-tomography**.

X-ray micro-tomography

Collect X-ray images of the sample as you rotate it through 180°

Use this series of images to “reconstruct” the 3D object

Penetrating power

Multiple angles

Courtesy of D. Parkinson (ALS)
1. Material Properties
   1. Phenomenological Properties
   2. Thermal transport
   3. Mass transport

2. Material Decomposition
   1. Oxidation
   2. Sublimation
   3. Spallation
Porous Microstructure Analysis (PuMA)

Technical Specifications

- Written in C++
- GUI built on QT
- Visualization module based on OpenGL
- Parallelized using OpenMP for shared memory systems

Domain Generation
- Artificial Material Generator
- Micro-tomography Import, Processing, and Thresholding

Visualization
- Marching Cubes
- OpenGL Surface Rendering

Material Properties
- Porosity
- Specific Surface Area
- Effective Thermal Conductivity
- Effective Electrical Conductivity
- Diffusivity / Tortuosity (Bulk and Knudsen)
- Representative Elementary Volume

Material Response
- Oxidation Simulations
- Transient Heat Transfer *

*Under Development

1. Material Properties
   1. Phenomenological Properties
   2. Thermal transport
   3. Mass transport

2. Material Decomposition
   1. Oxidation
   2. Sublimation
   3. Spallation
Effective Material Properties

**Porosity**
- Based on the grayscale threshold
- Sum of all void voxels over the total volume

**Specific Surface Area**
- Based on the Marching Cubes algorithm
- Overall surface area computed as a sum of individual triangle areas
Effective Thermal Conductivity

- Computes effective thermal conductivity using a finite difference method [Weigmann, 2006]
- BicGStab iterative method and FFTW used to solve linear system of equations [Sleijpen, 1993]
- Parallelized based on OpenMP
- Verified against complex analytical solutions
Effective Electrical Conductivity

• Computes effective electrical conductivity using a finite difference method [Weigmann, 2006]
• 1V voltage differential applied; solved with periodic boundary conditions
• BicGStab iterative method and FFTW used to solve linear system of equations [Sleijpen, 1993]
• Parallelized based on OpenMP
• Verified against complex analytical solutions
• Steady state current flow through a material can be determined

Steady state current flow through a carbon fiber material with an imposed voltage differential
Continuum

- Quantifies a material's resistance to a diffusive flux
- Solves for effective diffusivity using a finite difference method
- Valid for $Kn \ll 1$
- Solves diffusion equation using periodic boundary conditions

Ferguson et. al, Particle methods for tortuosity factors in porous media, 9th Ablation Workshop, Bozeman MT. (2017).
Diffusivity / Tortuosity – Random Walk

**Transitional/Rarified**

- Random walk method to simulate diffusion
- Mean square displacement method used to solve effective diffusion
- Valid for all Knudsen numbers.
- Knudsen number is varied by changing the molecular mean free path

\[
Kn = \frac{\bar{\lambda}}{\tilde{d}} = \frac{\text{mean free path}}{\text{characteristic length}}
\]

- Surface collisions based on marching cubes triangles with diffuse reflections used

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Ferguson et. al, Particle methods for tortuosity factors in porous media, 9th Ablation Workshop, Bozeman MT. (2017).
Micro-Scale Oxidation Simulations

- Particle-based oxidation method
- Diffusion simulated through random walks
- Collision detection with linear interpolation method
- Sticking probability method for material recession
- Verified against analytical solutions for single fiber

Material Generation

Random Fiber Structures

Packed Sphere Beds

Periodic Foams
Challenges: Segmentation

Raw Grayscale Data

Segmented Data
Thresholding Approach

Normalized counts vs. Gray-scale level

Black to White transition in the cutoff region
When Thresholding Works Well

1. Two phase materials
2. Direction is irrelevant
3. High contrast between phases
When Thresholding Fails

1. Multi phase materials
2. Direction is important
3. Low contrast between phases
Example 1: Woven Materials

Why thresholding fails

Need to separate the weave directions from one another for modeling purposes
Example 1: Woven Materials
Example 1: Woven Materials
Example 1: Woven Materials

Training Data Available

1. 6-ply weave
2. 4-ply weave
3. 12-ply weave

Manually Segmented
Example 2: Asteroid Samples

Why thresholding fails

Multiple phases with overlap in grayscale value. Can’t distinguish between phases through thresholding methods
Example 2: Asteroid Samples

Matrix

Not a crack

Not a crack

Not a crack

Iron/nickel

crack

crack
Prediction of sun spots
Prediction of sun spots
Prediction of sun spots

Unknovns

1. How to apply ML/AI techniques to time-series data

2. Would processing velocity data give more information: gradients, curl, etc.
Questions?

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