Proton Radiography Peers into Metal Solidification

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Solidification: chemical inhomogeneity
Solidification: chemical inhomogeneity
Solidification: pattern formation

- PLANAR
- CELLS
- DENDRITES

$100 \mu m$
Solidification: relationship to properties
Solidification: persistence

Solidification

• Experienced by almost all metals and alloys

• Influences:
  – Grain size and shape
  – Chemical homogeneity
  – Defect type and density
  – Residual stresses
Multi-scale Prediction and Control of Metal Alloy Solidification Dynamics
Solidification: multi-scale

- **Atoms**
  - Atom Probe Tomography
  - Electron Microscopy
  - X-ray radiography
  - Spectroscopy
  - Electron Back-Scattered Diffraction
  - Proton radiography

- **Interface pattern**
  - X-ray radiography (2D/3D) - Si 310 directional solidification

- **Grain structure**
  - Proton radiography S1/S2 cooling
  - High purity Cu cooling

- **Cast part**
  - Phase-field
  - Dendritic Needle Network
  - Cellular Automaton
  - Continuum
  - Plasticity

**Simulations**

- [Drury, A., Kane, M., Mat Sci Eng R 2003]
- [Drury et al., in preparation]
- [Drury et al., JOM 2016]
- [Gander et al., JOM 2013]
- [Oliver and J.M., JOM 2013]

**Observations**

- [Marques, J., Fluor, Mat Sci Eng R 2010]
- [Herzinger et al., Acta Mater. 2000]
- [Tokahashi, Gandin, Rappaz, Acta Mater. 2000]
### pRad: overview

<table>
<thead>
<tr>
<th></th>
<th>X-rays</th>
<th>Protons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contrast dependence</td>
<td>(Atomic number)$^4$</td>
<td>Mass density</td>
</tr>
<tr>
<td>Sample thickness</td>
<td>~100 µm</td>
<td>µm to cm</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>0.5 to 2 µm</td>
<td>25 to 280 µm</td>
</tr>
<tr>
<td>Field of view</td>
<td>1 to 5 mm</td>
<td>17 to 120 mm</td>
</tr>
<tr>
<td>Exposure time</td>
<td>ms to s</td>
<td>ns to µs</td>
</tr>
<tr>
<td>Frame rate</td>
<td>0.1 to 1000 Hz</td>
<td>20 Hz (for statics)</td>
</tr>
</tbody>
</table>
pRad results: microstructure formation

Proton Imaging
pRad at LANSCE at LANL

X-ray Imaging
APS at ANL

http://www.nature.com/srep/2013/130619/srep02020/full/srep02020.html
pRad results: microstructure formation
pRad to visualize casting process
pRad to visualize casting process

Liquid speed (m/s)

0.00  0.25  0.50  0.75  1.00

750,000 s

0.00 s

10 mm
pRad to visualize casting process
pRad to visualize casting process

80wt% Bi – 20wt% Sn
(low viscosity)

20wt% Bi – 80wt% Sn
(high viscosity)
pRad to visualize casting process

80wt% Bi – 20wt% Sn (low viscosity)

20wt% Bi – 80wt% Sn (high viscosity)
pRad to visualize casting process
pRad to visualize casting process
From $\mu$m to m: Bridging Length Scales in Metal Alloy Casting Simulations

**Goal:** Add and validate a microstructural model into Truchas (an ASC code for finite volume modeling of metal casting)

- pRad gives the fluid flow and macroscopic solidification behavior to constrain Truchas
- Truchas predicts the thermal history and microstructural variations
- Dendritic needle network modeling predicts local microstructural evolution, informed by Truchas temperatures
- Ex-situ characterization is used to validate the microstructural models
- Microstructural characteristics are compared to mechanical properties

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Future work: x7 magnification

Transmission Image

Grad(Image)

3 mm-thick tungsten resolution plate

3 mm-thick tungsten resolution plate
Future work: x7 magnification

<table>
<thead>
<tr>
<th></th>
<th>Before</th>
<th>After</th>
</tr>
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<tbody>
<tr>
<td>$\sigma_x$ ((\mu m))</td>
<td>23</td>
<td>66</td>
</tr>
<tr>
<td>$\sigma_y$ ((\mu m))</td>
<td>26</td>
<td>28</td>
</tr>
</tbody>
</table>
Future work: time resolved proton tomography

Example x-ray image of 3D dendritic growth

4-axis motion control Bridgman furnace

Tomographic reconstruction software (Time-Interlaced Model-Based Iterative Reconstruction (TIMBIR))
Acknowledgements

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• pRad Team at LANL

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