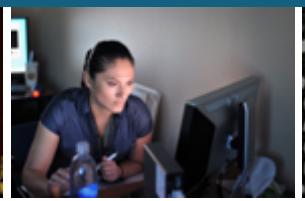
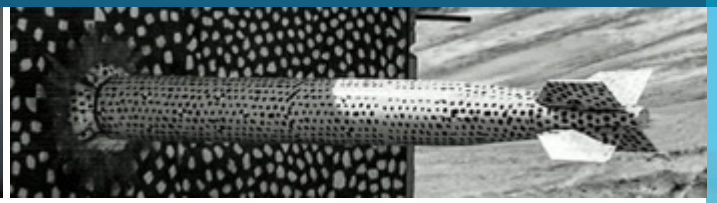
SAND2022-5919C

Sandia National Laboratories

Probing the effects of microstructure on material strength in additively manufactured 304L stainless steel through Richtmeyer-Meshkov instability experiments





JOWOG 32 Mat, Los Alamos National Laboratory

May 11, 2022

Brittany Branch, Justin Brown, Tim Ruggles, Stewart Silling, John Mitchell Dave Adams and Paul Specht

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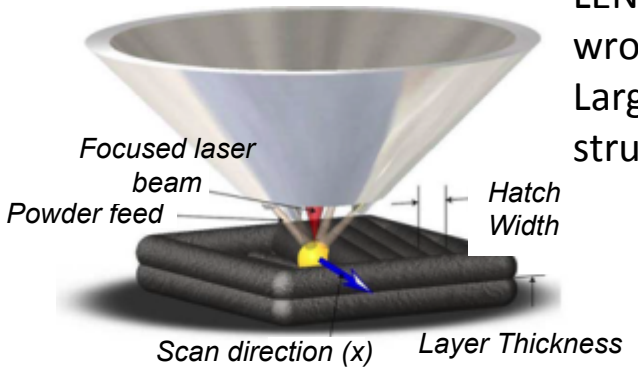
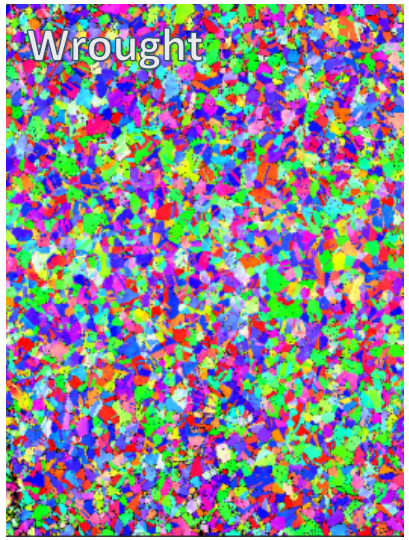
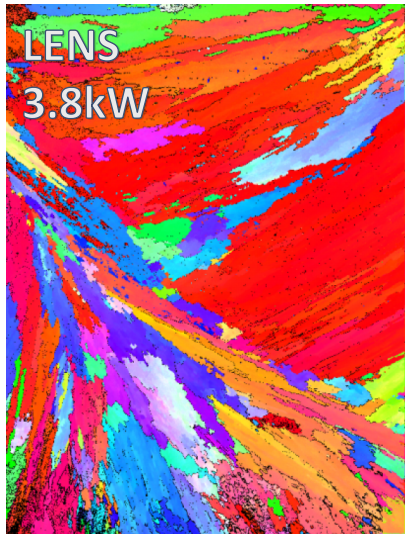
Background & Motivation

A comprehensive understanding of material behavior at high pressures and strain rates is needed in order to validate material models and inform the development of material models that are microstructurally aware to predict material properties and performance.



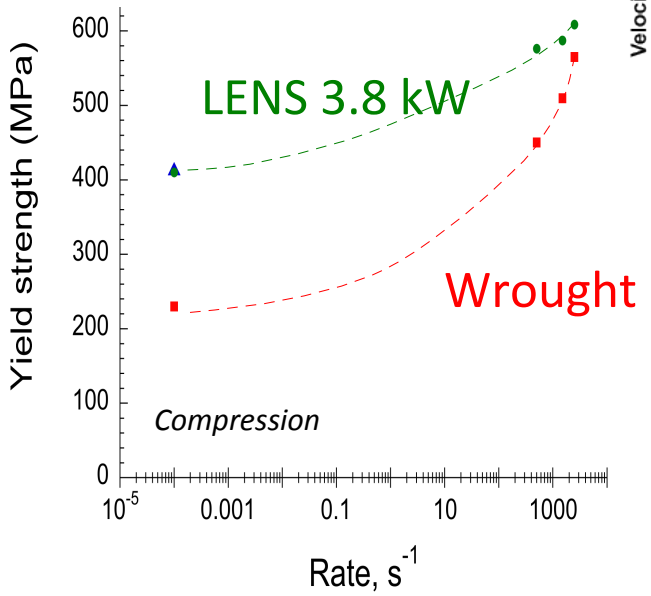
LENS® microstructure differs dramatically from wrought 304L microstructure - Highly textured, Large grain size, High residual stress, Subgrain structure



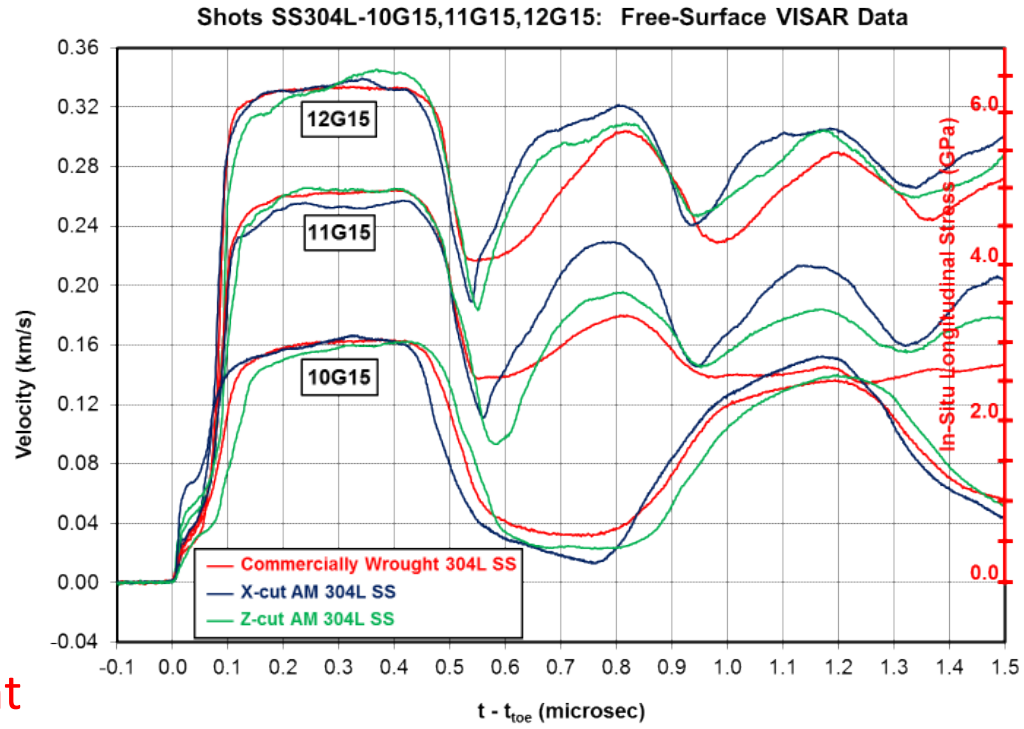


1.0 mm

Increase in strength is reduced (compared to wrought) when tested at increasingly high strain rates.



J.L. Wise,

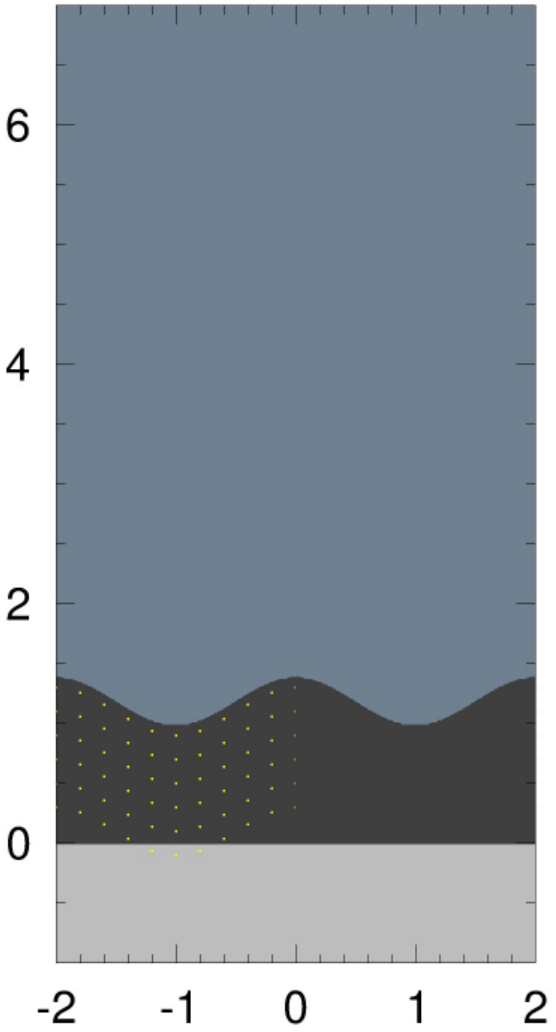


Spall strength:
X-cut (3.27 – 3.36 GPa)
Z-cut (3.71 – 3.91 GPa)
Wrought (2.63 – 2.88 GPa)

Measuring Material Strength

$$A = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$$

For $A<0$ ($\rho_1>\rho_2$), can invert

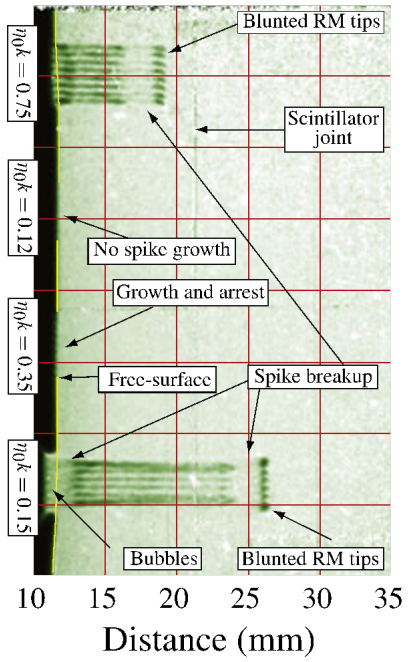


Dynamic Interface Instabilities

- Arise at interfaces between dissimilar materials i.e. gases, liquids, solids
- Shear, gravitational and shock instabilities
- Instabilities probe surface tension, viscosity and strength effects of materials behavior
  - ➢ Kelvin-Helmholtz Instability – shearing
  - ➢ Rayleigh-Taylor Instability – gravitational
  - ➢ Richtmyer-Meshkov Instability - shock

Dimonte et al. (2011). Phys. Rev. Let.

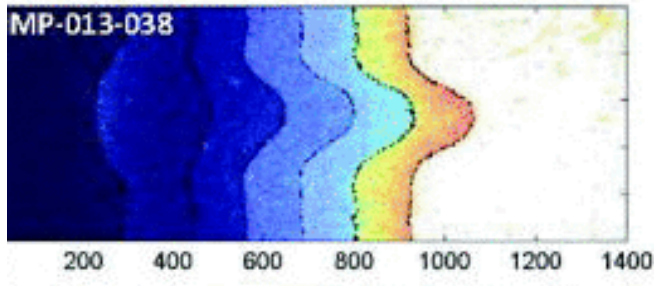
Buttler et al. (2012). J. Fluid Mech.



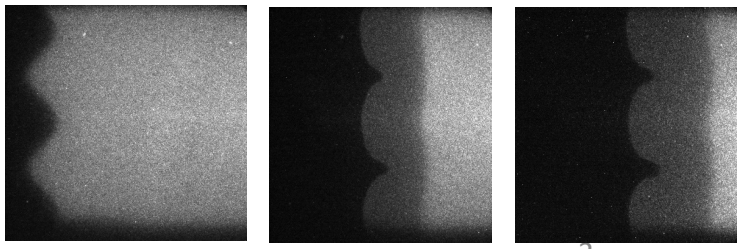
Proton Radiography

Vacuum, $A=-1$

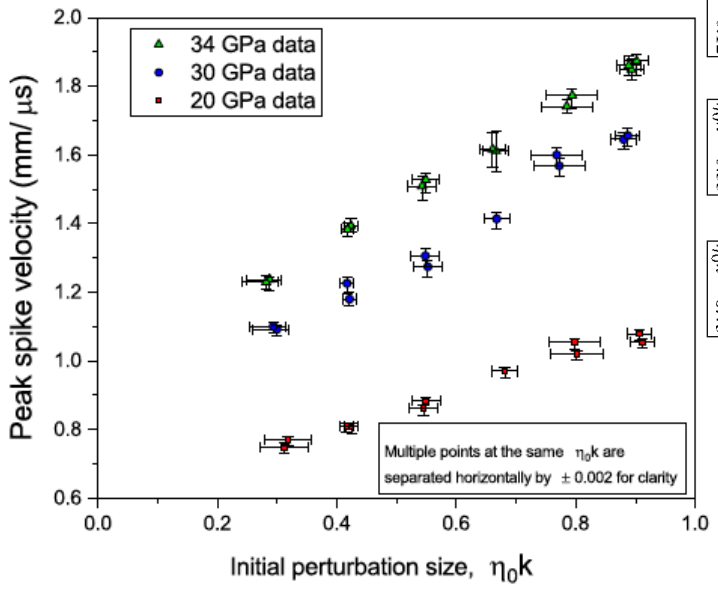
$\rho_2=0$



Jensen, et al. J. Applied Phys.



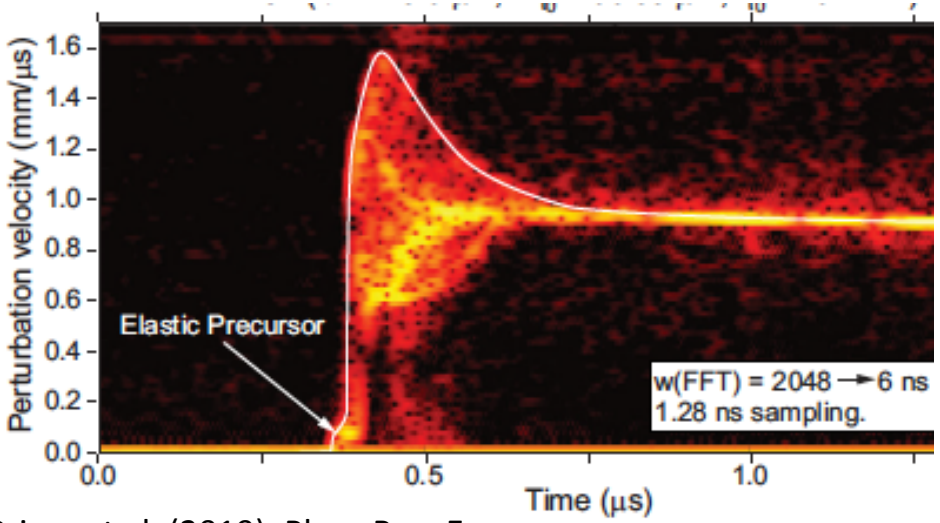
X-ray PCI Hudspeth, et. al SAND 2019-10277.



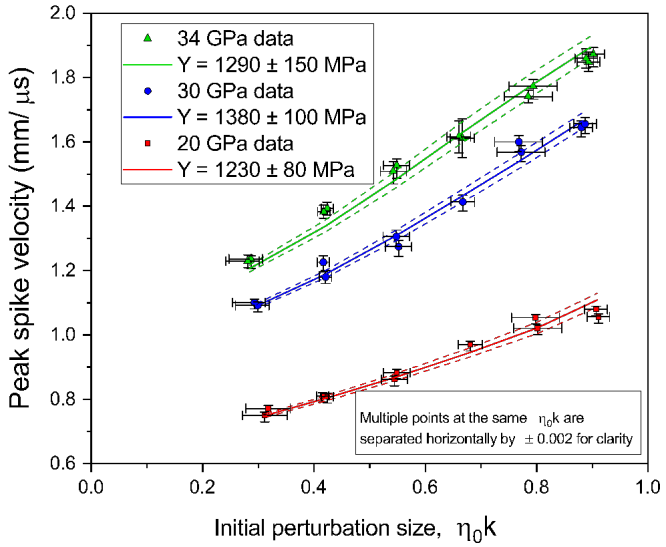
Prime et al. (2019). Phys. Rev. E

Velocimetry and Radiography Diagnostics

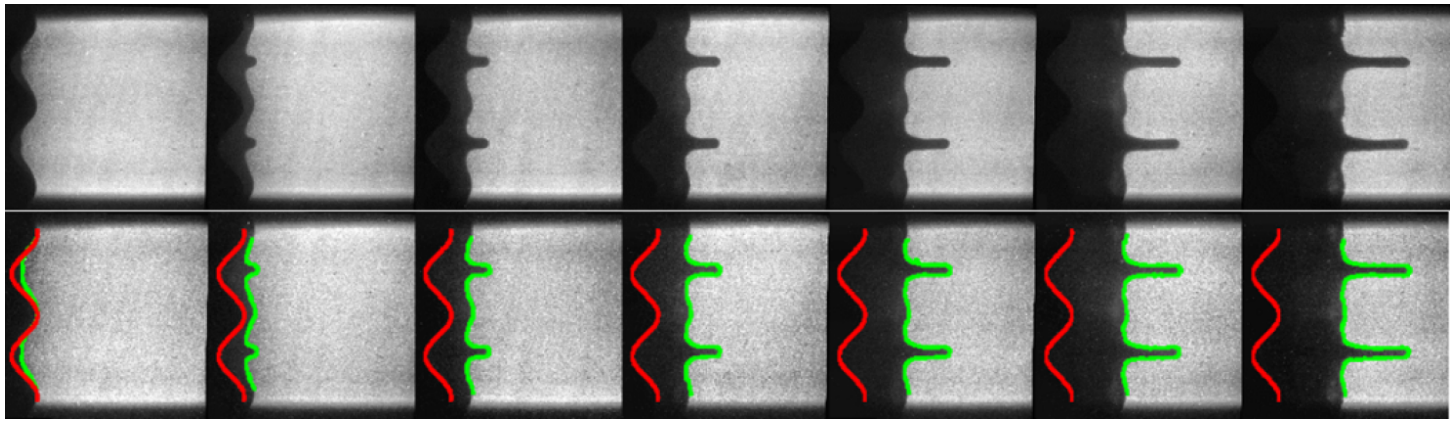
Photonic Doppler Velocimetry



Prime et al. (2019). Phys. Rev. E



Propagation Based Phase Contrast Imaging



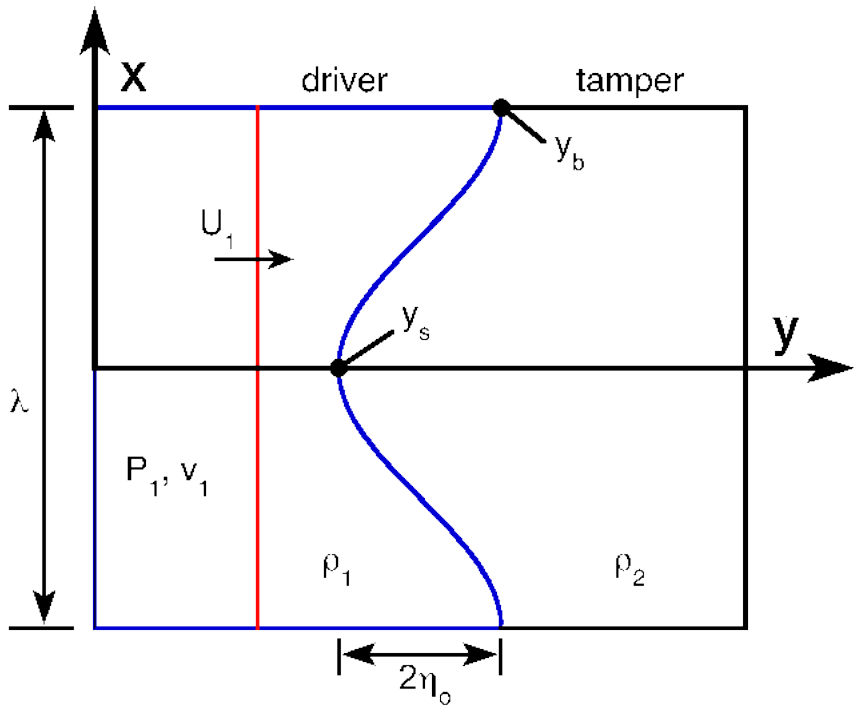
Olles et al. (2019). Soc. Expt. Mech.

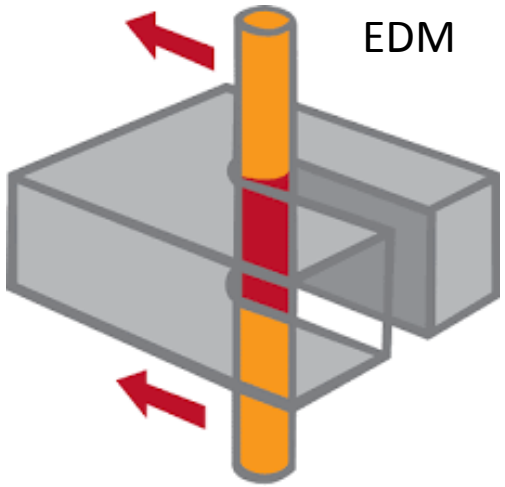
Real-time characterization of shockwave propagation allows for more direct comparison to simulations.

- Dynamic Interface Instabilities – probe surface tension, viscosity and strength effects of materials behavior.
- Microstructural effects on dynamic performance.

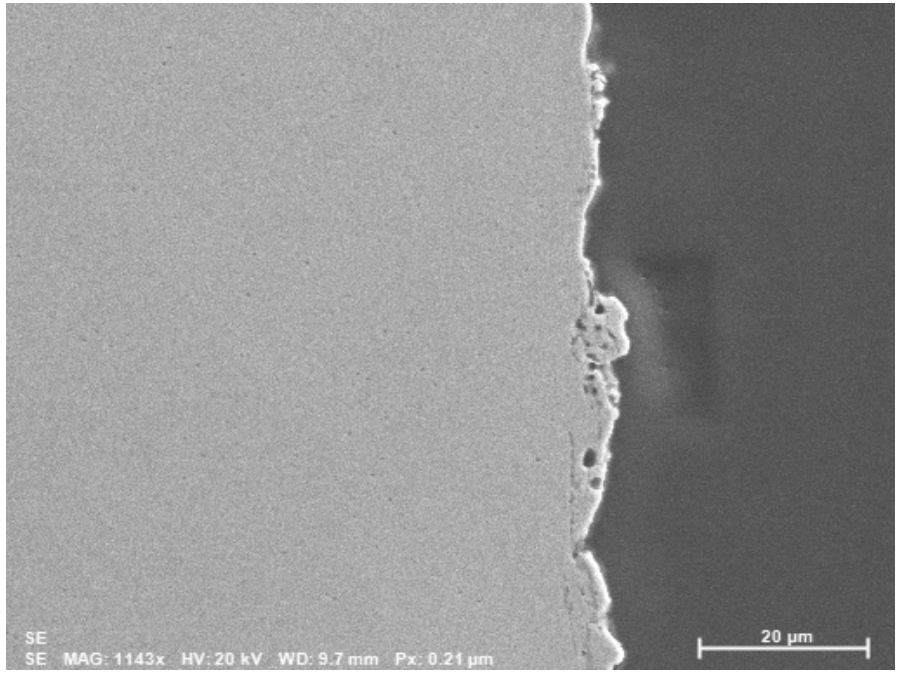
In-situ phase contrast imaging coupled to dynamic loading platforms enables observation of transient variations in shockwave dynamics that would not be detected using traditional velocimetry diagnostics (limited to surface measurement).

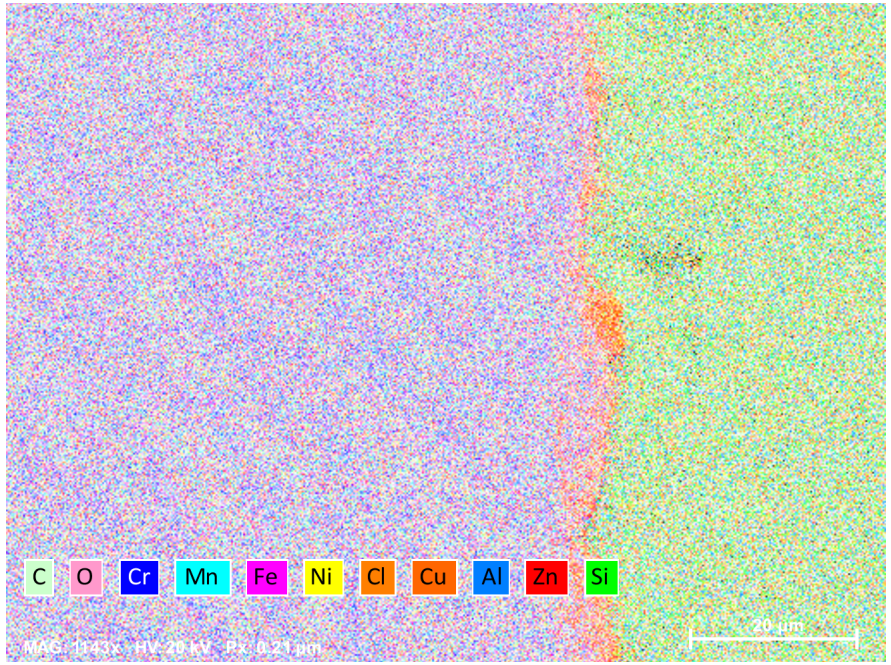
Typical RMI Geometries





$$\eta_o k = \frac{2\pi}{\lambda}\eta_o$$

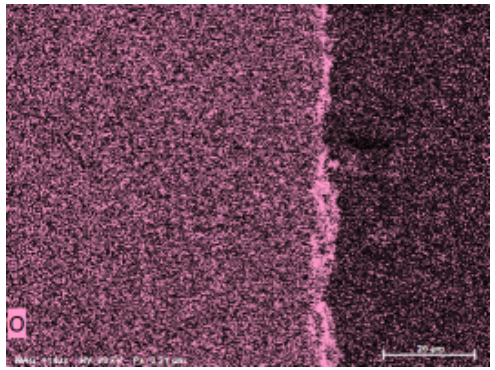


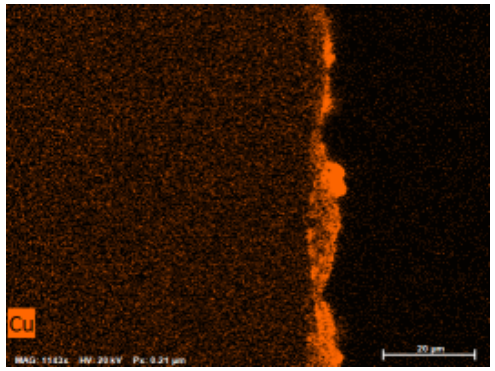


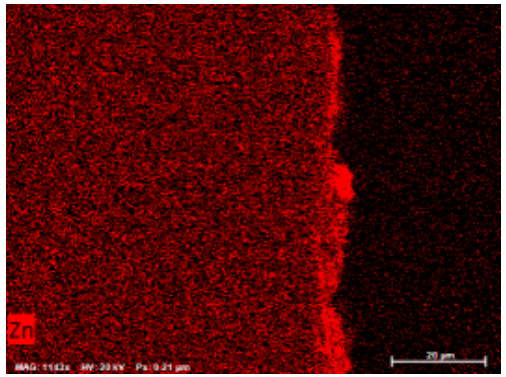
- Perturbations specified by non-dimensional geometry with wavenumber (k) defined by wavelength (λ) and amplitude (η_o).
- Sinewave Perturbations machined by electro-discharge machining.
  - EDM - recast layer and heat affected zone (HAZ).
  - Surface effects and contaminates altering surface tension, viscosity and strength → change material properties!

Characterization of Brass EDM Surface

Dave Adams (SNL, 1832)





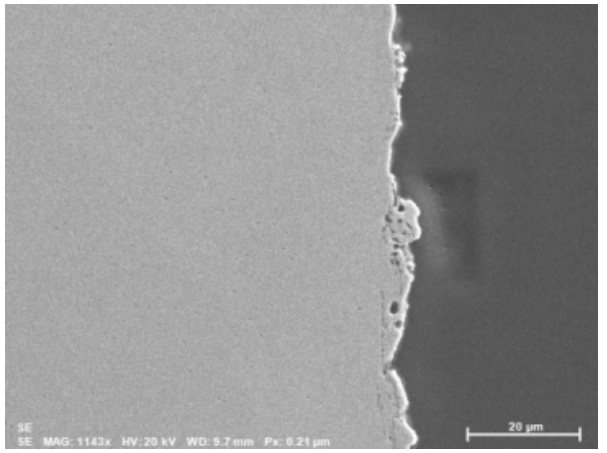


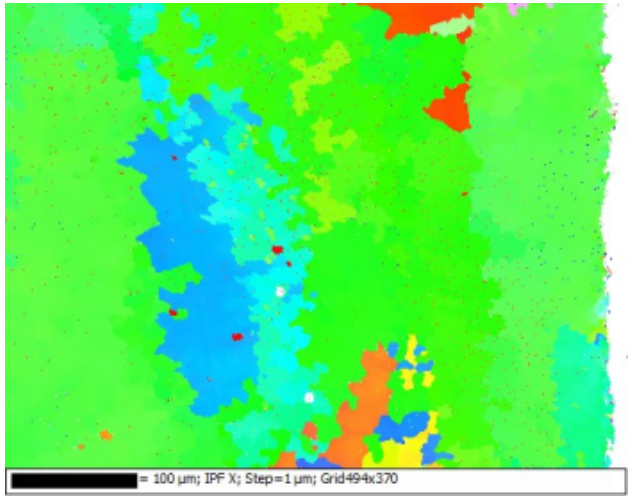
Historically…

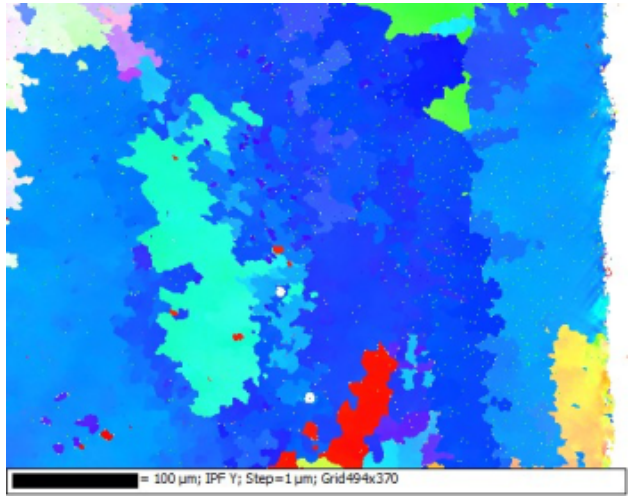
- Recast layer contain molten metal particles re-deposited on surface.
- HAZ and recast layer can contain microcracks leading to stress failures.

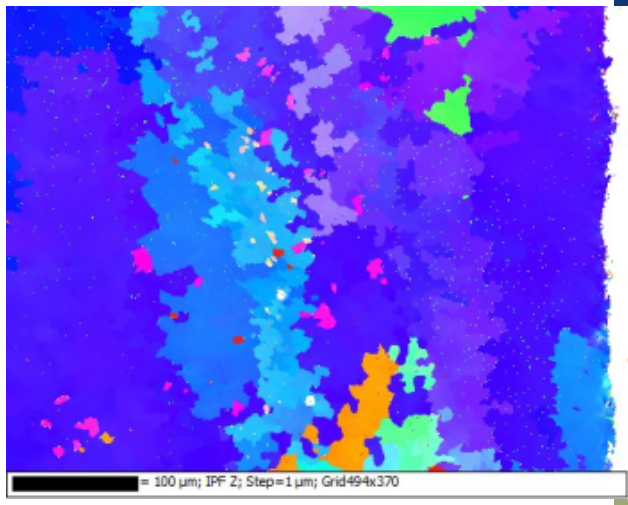
Observed Here…

- Minimal recast layer (<5 microns)
- Micro-cracks are non-existent
- Slight variation in microstructure 10-20 microns deep.





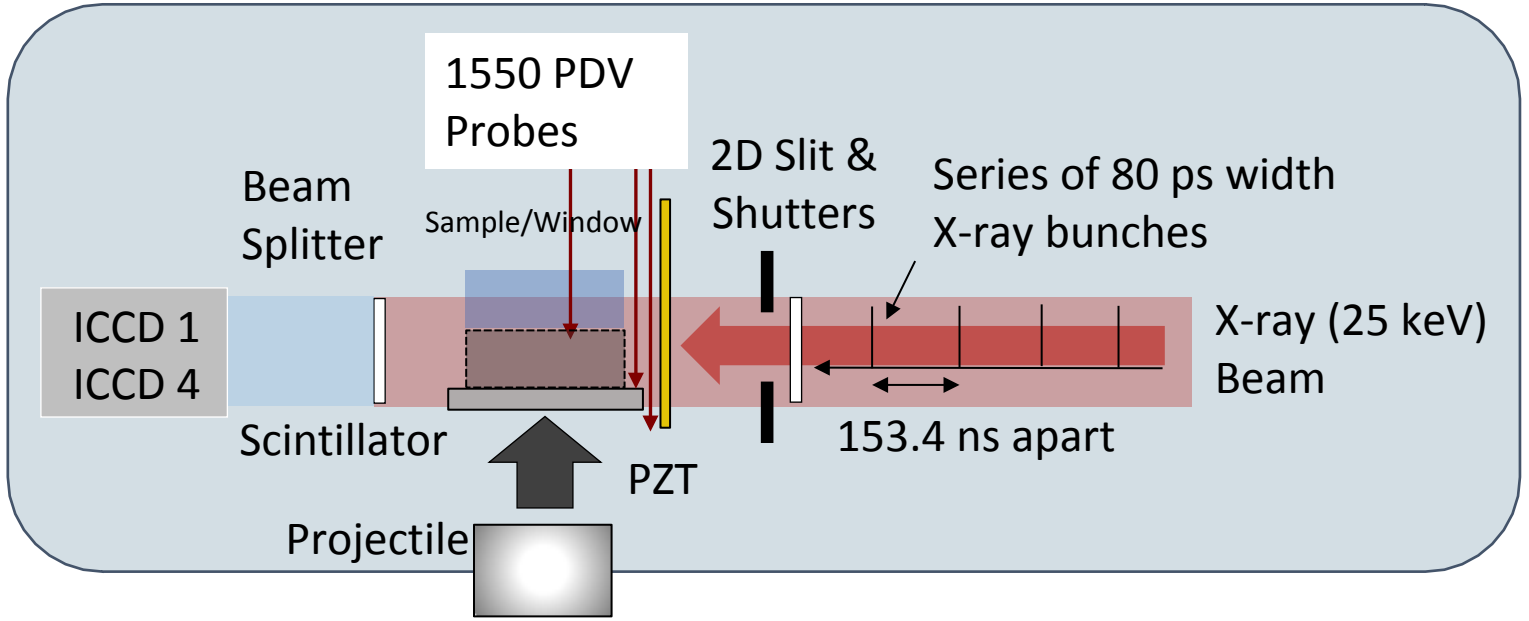




RMI Experiments

Advanced Photon Source

DCS a user facility (WSU operated) designed to optimally link dynamic compression platforms to a dedicated synchrotron beamline.



- Single- and two-stage gas guns, laser shock capability, multi-event hutch
- Beam line is optimized to allow for single pulse (80-ps width) X-ray imaging and diffraction measurements on many materials
- Focus on time-resolved, in-situ diffraction and imaging measurements; simultaneous continuum measurements

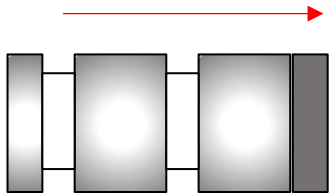
Typical Operating Energy ~23 keV

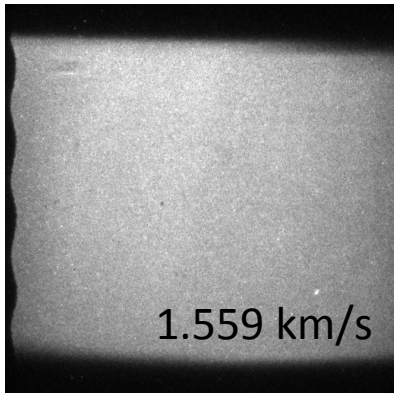
8 Frame Temporal Resolution at 153.4 ns

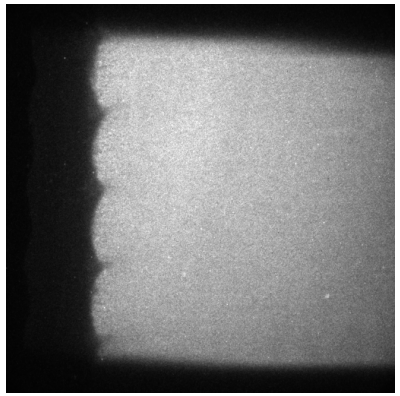
Beam Size 12.6 x 7.7 microns

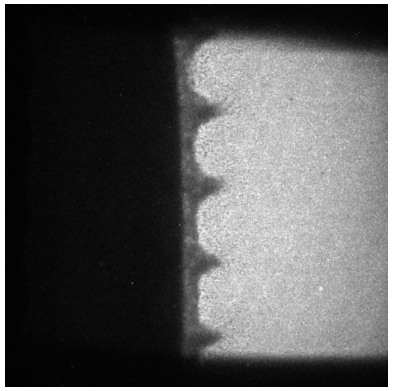
FOV of ~1.7-2.2 mm^2

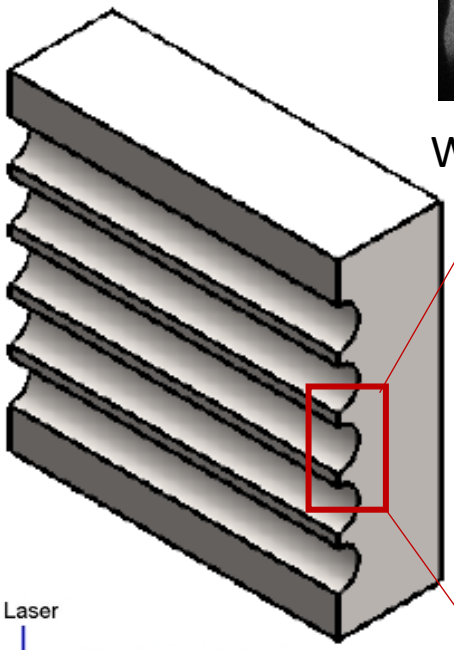
What Role Does Microstructure Play?



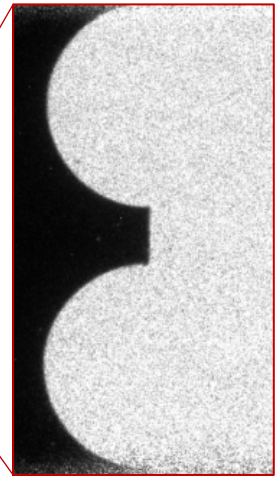


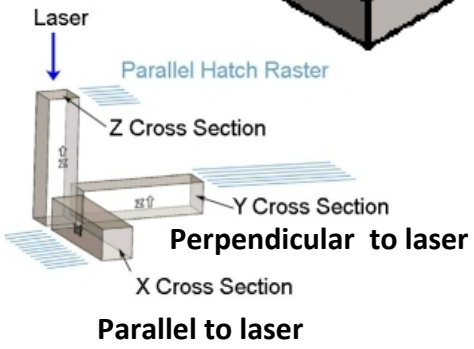


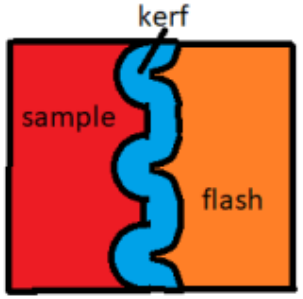


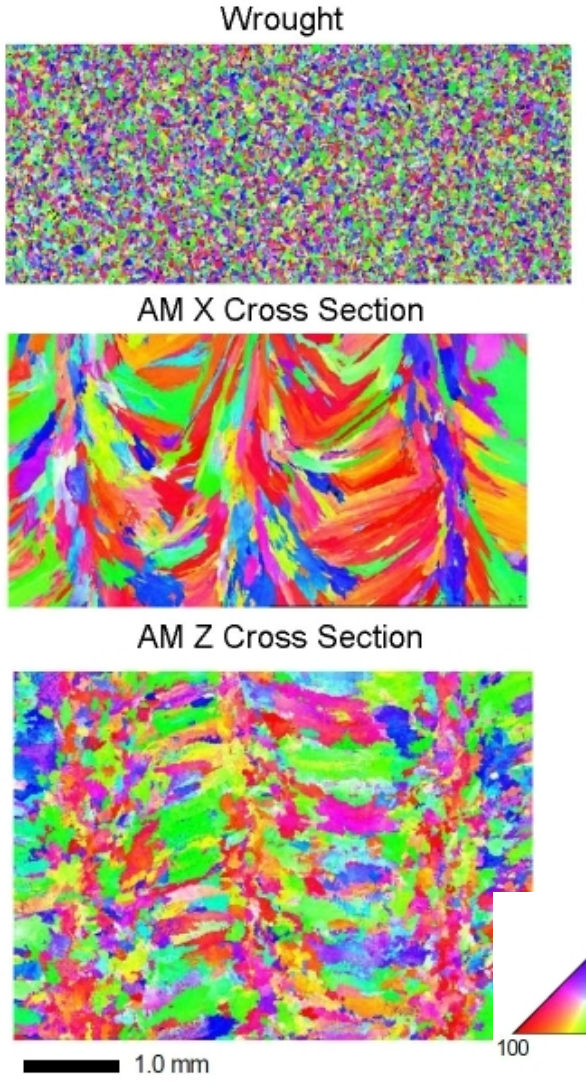


Wavenumber = 0.63



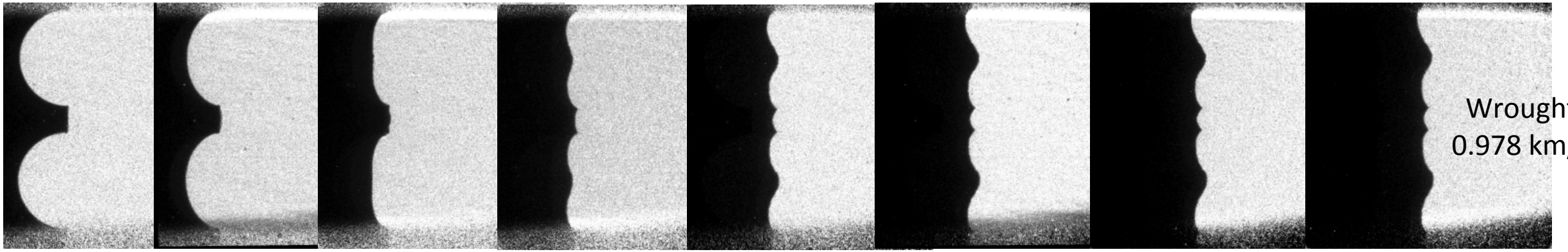




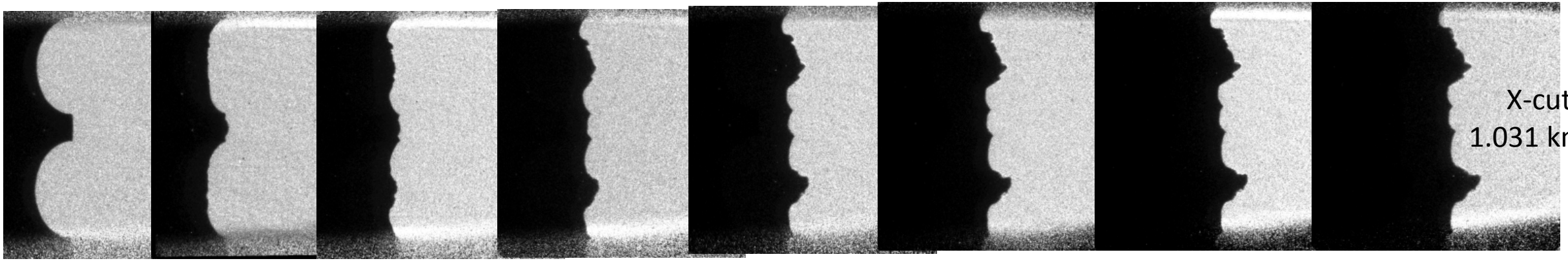


- Perturbations on the scale of individual grains → no difference in response
- New geometry incorporates multiple grains at point of instability formation → develop understanding of how grain interactions affect strength.
- Mapping of grains in immediate proximity → microstructurally aware models

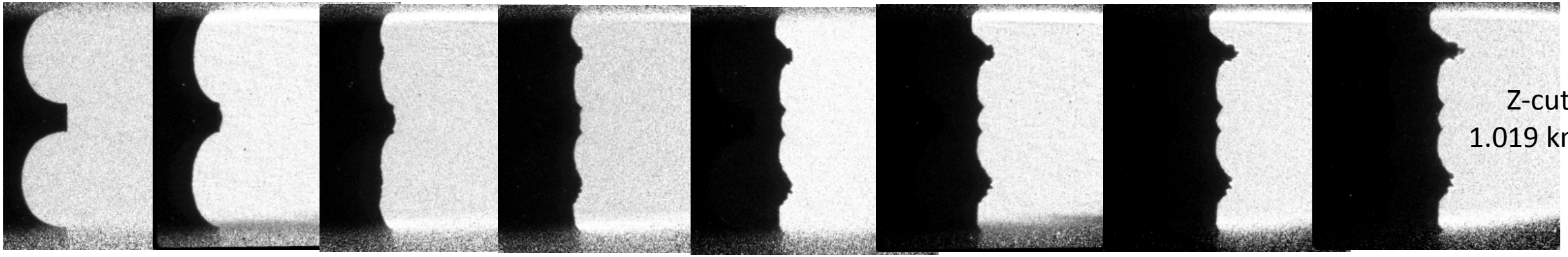
Shock Compression Experiments (~21.1 GPa)



Wrought
0.978 km/s

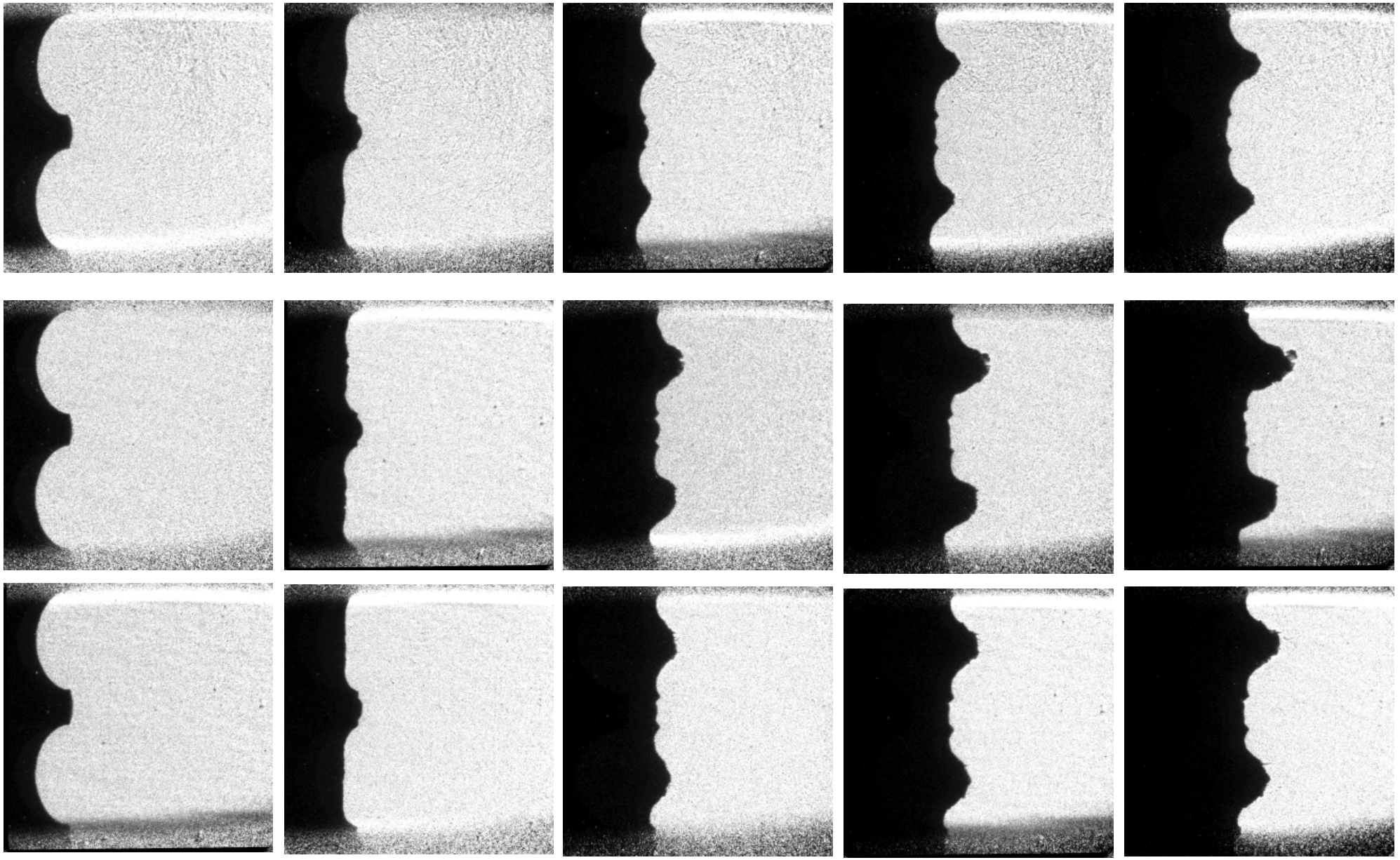


X-cut
1.031 km/s



Z-cut
1.019 km/s

Shock Compression Experiments (~24.5 GPa)

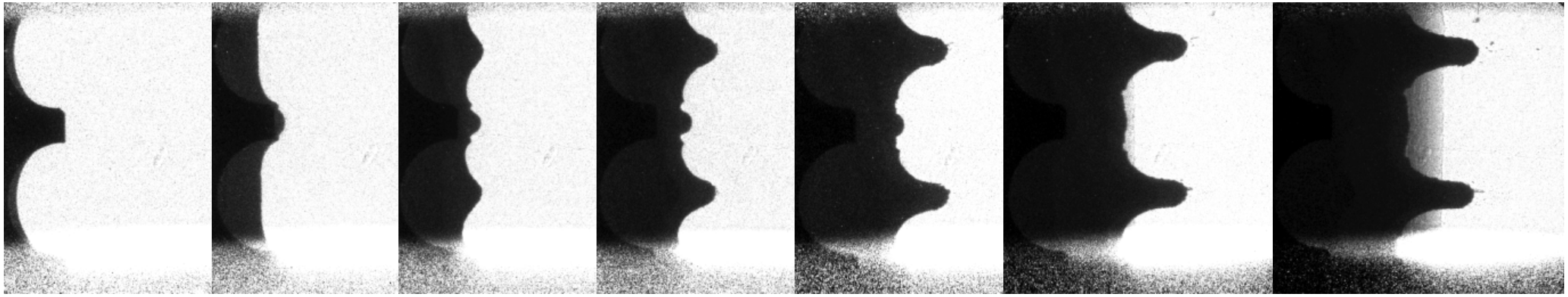


Wrought
1.153 km/s

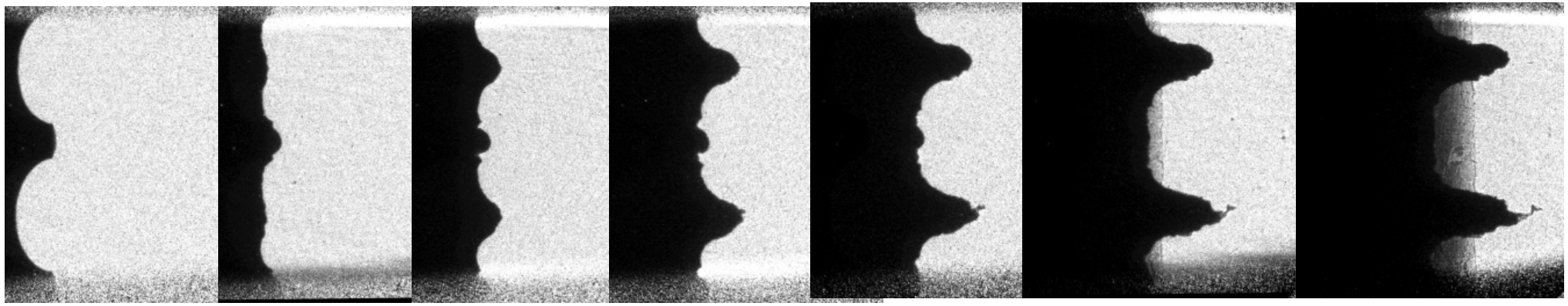
X-cut
1.173 km/s

Z-cut
1.124 km/s

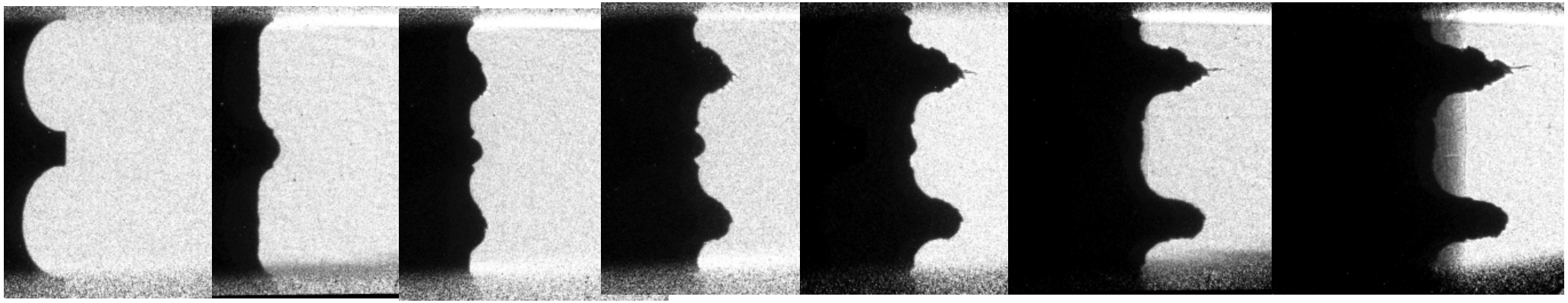
Shock Compression Experiments (~28.5 GPa)



Wrought
1.3 km/s



X-cut
1.314 km/s

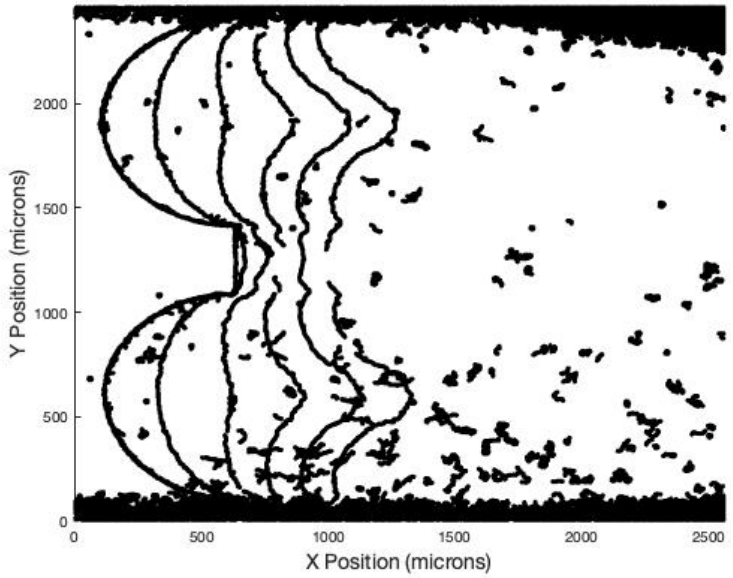


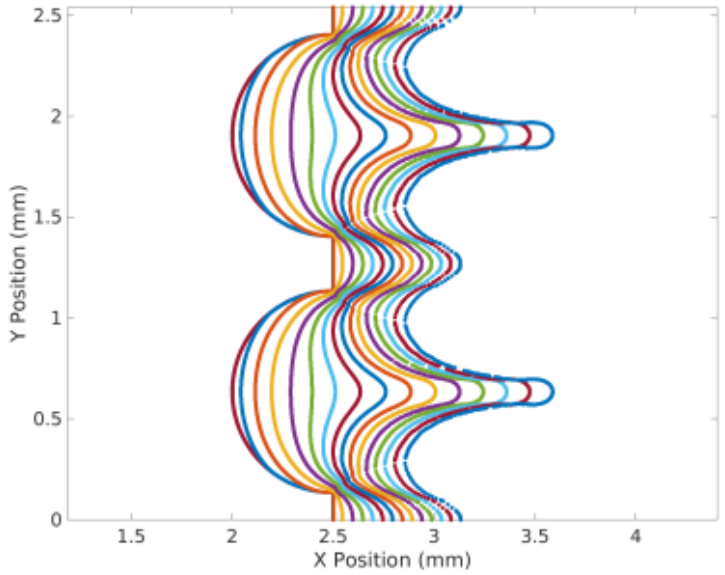
Z-cut
1.303 km/s

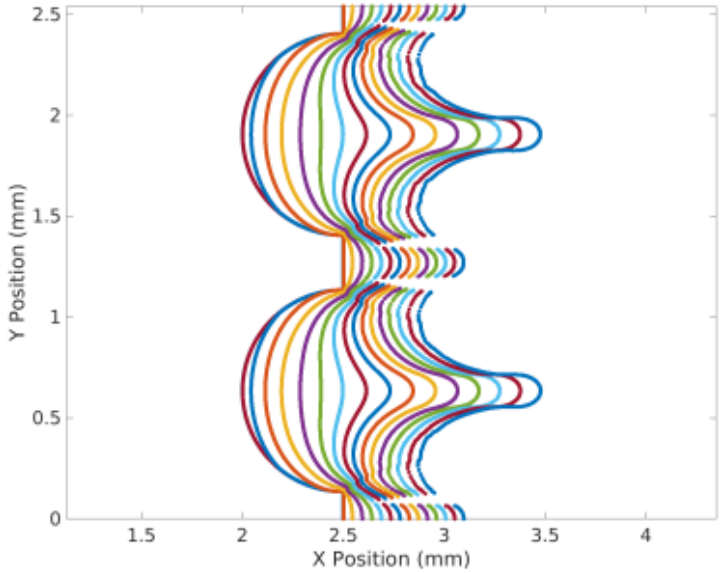
Continuum Modeling

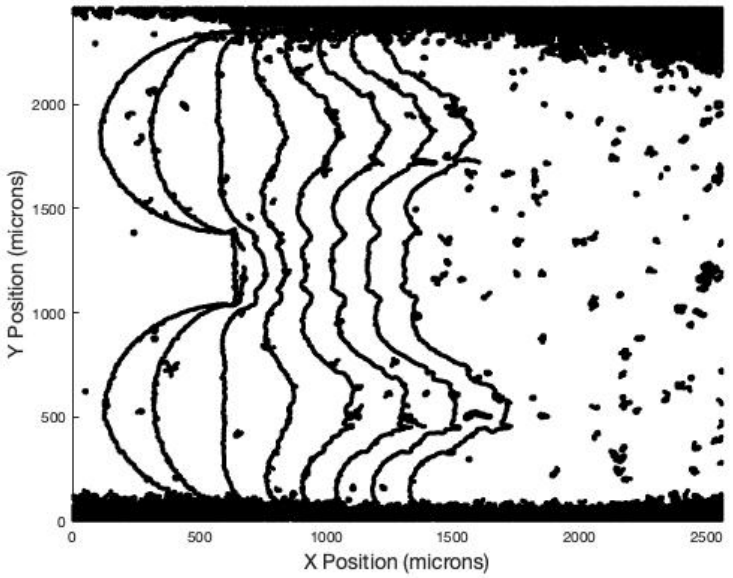
Sesame 4271, EEP
Yield Strength 400-1000 MPa

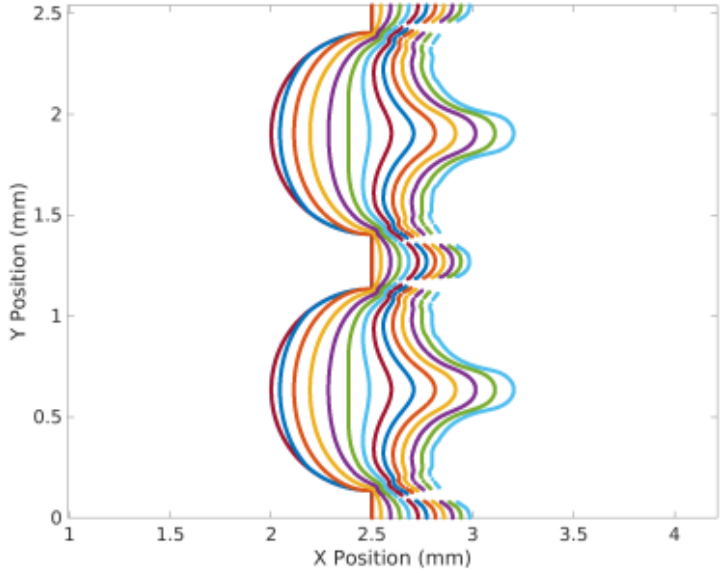
Justin Brown (SNL, 1646)

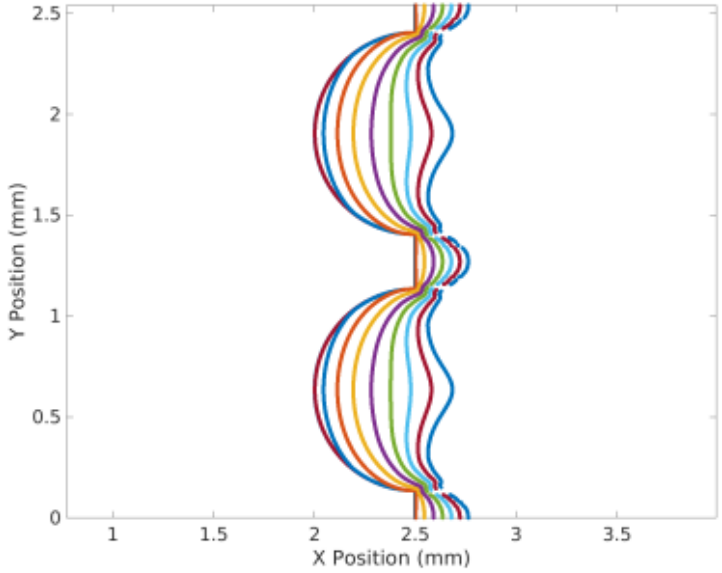










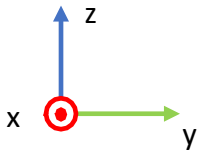


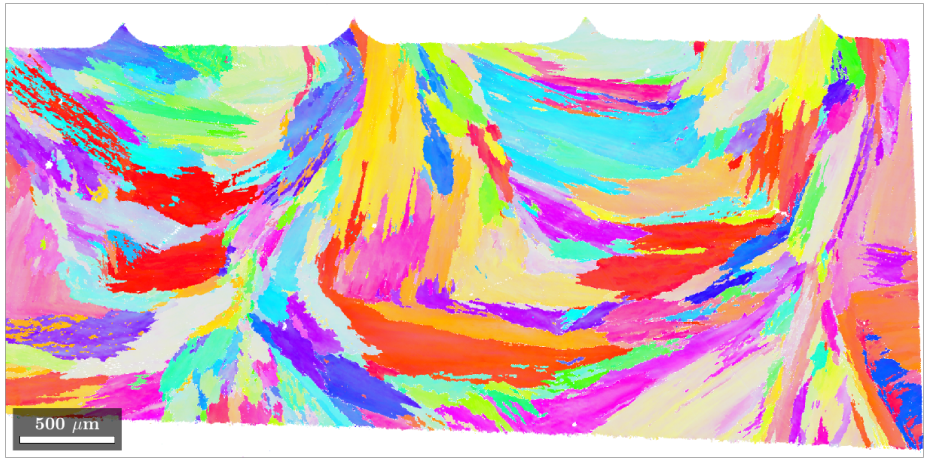
Incorporating Microstructure

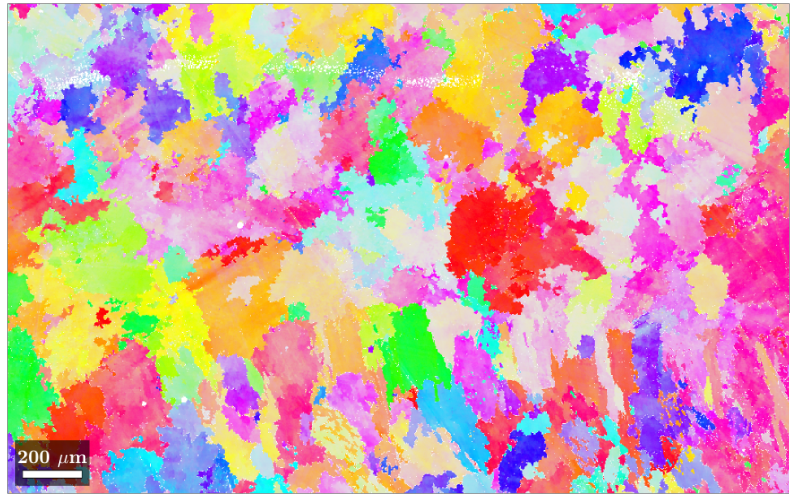
Tim Ruggles (1819), John Mictchell (1444) &
Justin Brown (1646)

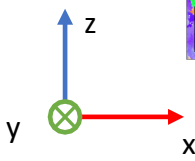
EBSD Materials Characterization

Z1

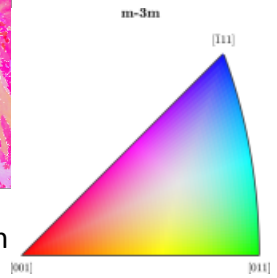




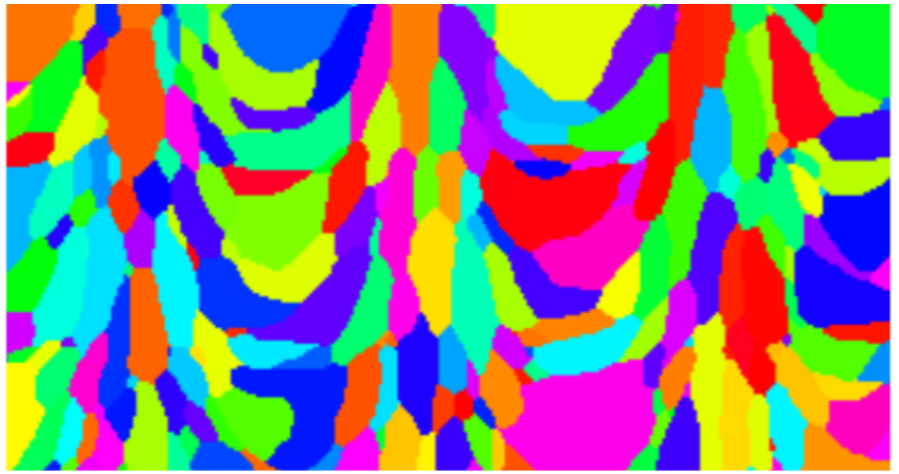




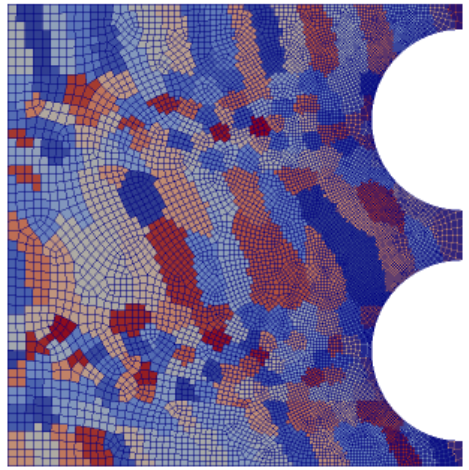
All IPF color maps are given with respect to the z direction



SPPARKS AM Microstructure Simulations



Microstructurally Aware ALEGRA Simulations



Mesh of grain-based material properties does not work properly for non-cartesian meshes

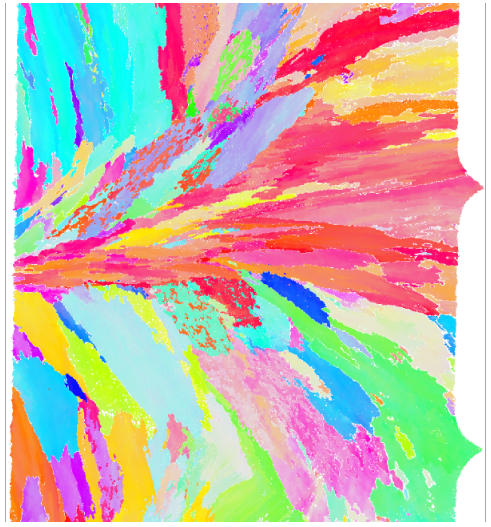
Work in Progress!

Modeling the Effect of Microstructure and Failure

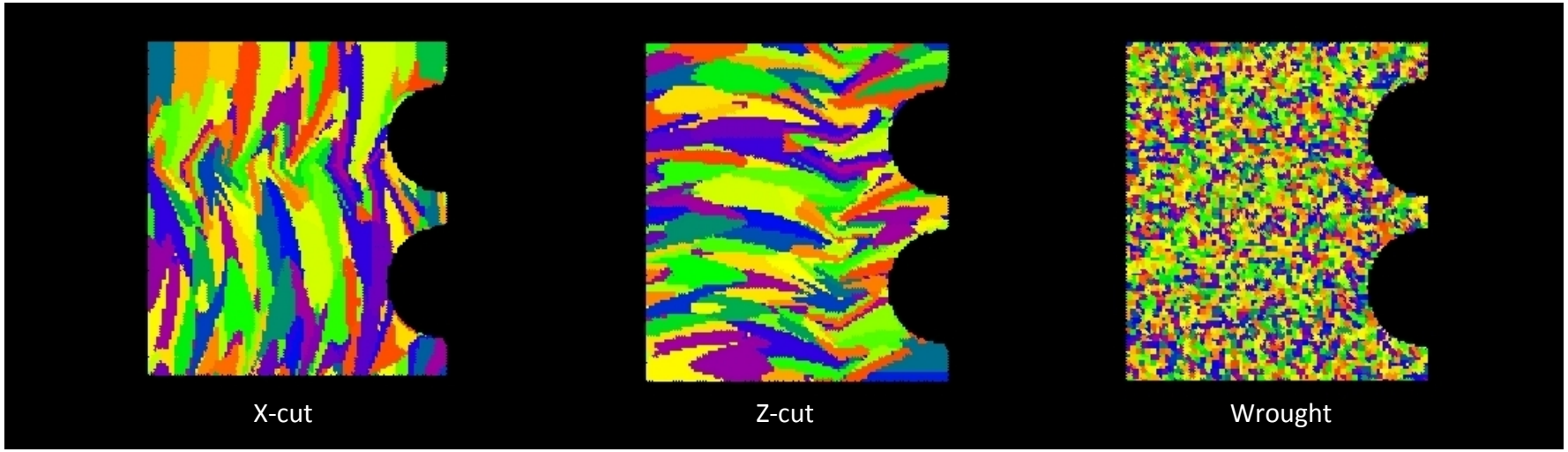
Stewart Silling (1444)

Method

- 3D meshless peridynamic code Emu[1].
- Voronoi cells are mapped into grain shapes representative of AM.
  - Grain fracture criteria follow a random distribution.
- Crystal plasticity model[2] is used with random lattice orientations.
  - Includes strain hardening, rate dependence, thermal softening, damage
- Spall Kinetics model is used (but it turns out that spall does not occur significantly near the jets).
- 3 forms of 304-L stainless steel are impacted at 1150m/s:
  - X-cut AM, Z-cut AM, Wrought



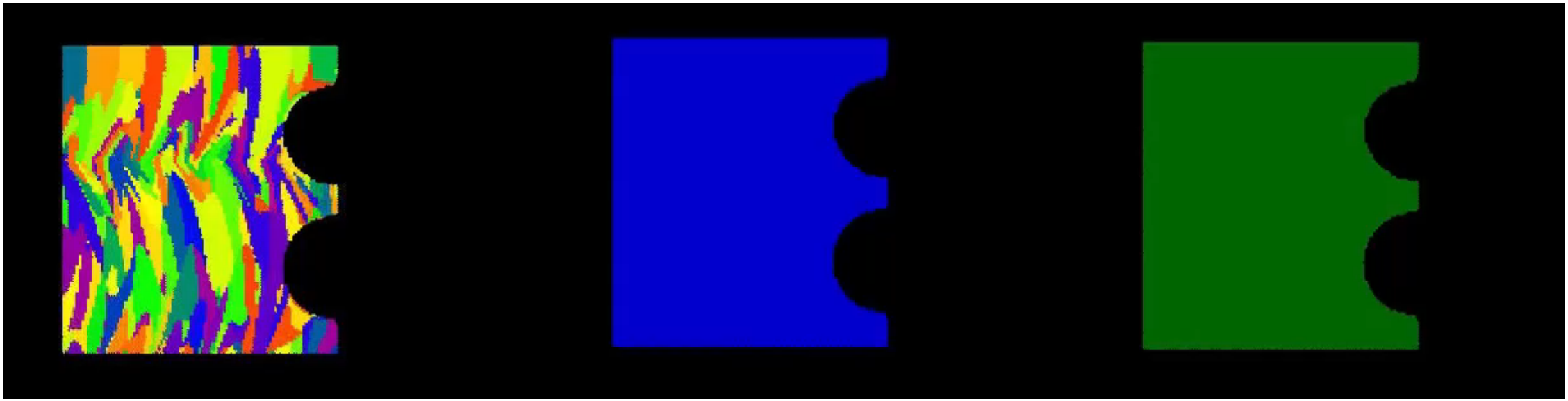
Artificial microstructures



1. S. A. Silling et al., *Intl. Journal of Impact Engineering* (2017)
2. P. J. Maudlin and S.K. Schiferl, *Computer methods in applied mechanics and engineering* (1996)

Microstructural Deformation and Stress (X-cut)

Stewart Silling (1444)



Grains

Von Mises (shear) stress
White = 1200MPa

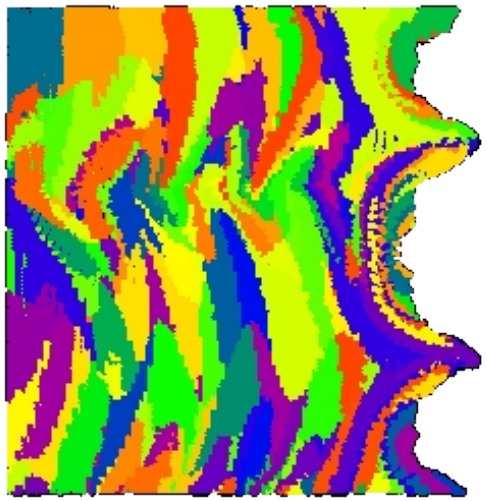
Tensile strain
White = 300%

- Shear stress is large as the jets form.
- Tensile strain becomes large within the jets as they grow.

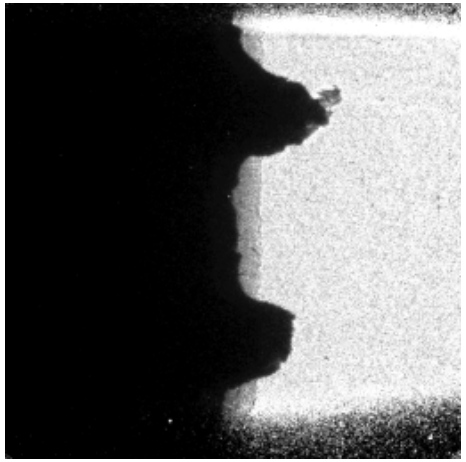
Jet Shape for Different Impact Directions

Stewart Silling (1444)

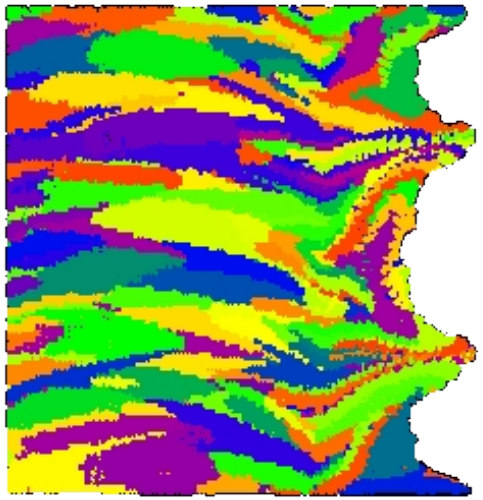
X-cut



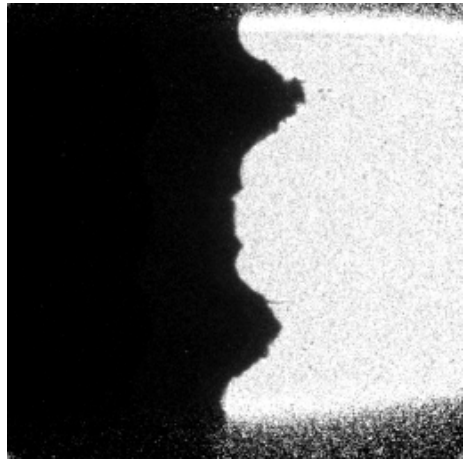
1200 ns after impact



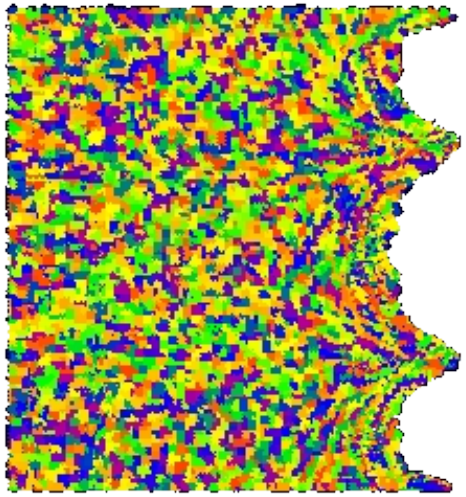
Z-cut



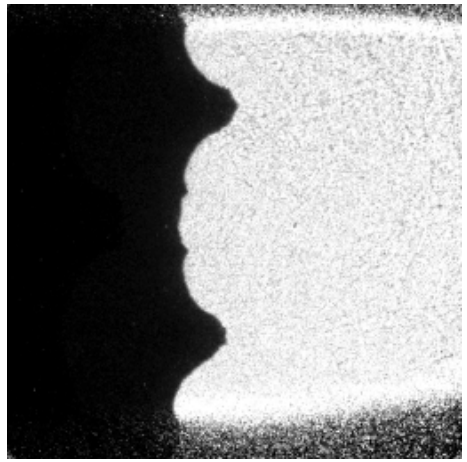
1200 ns after impact

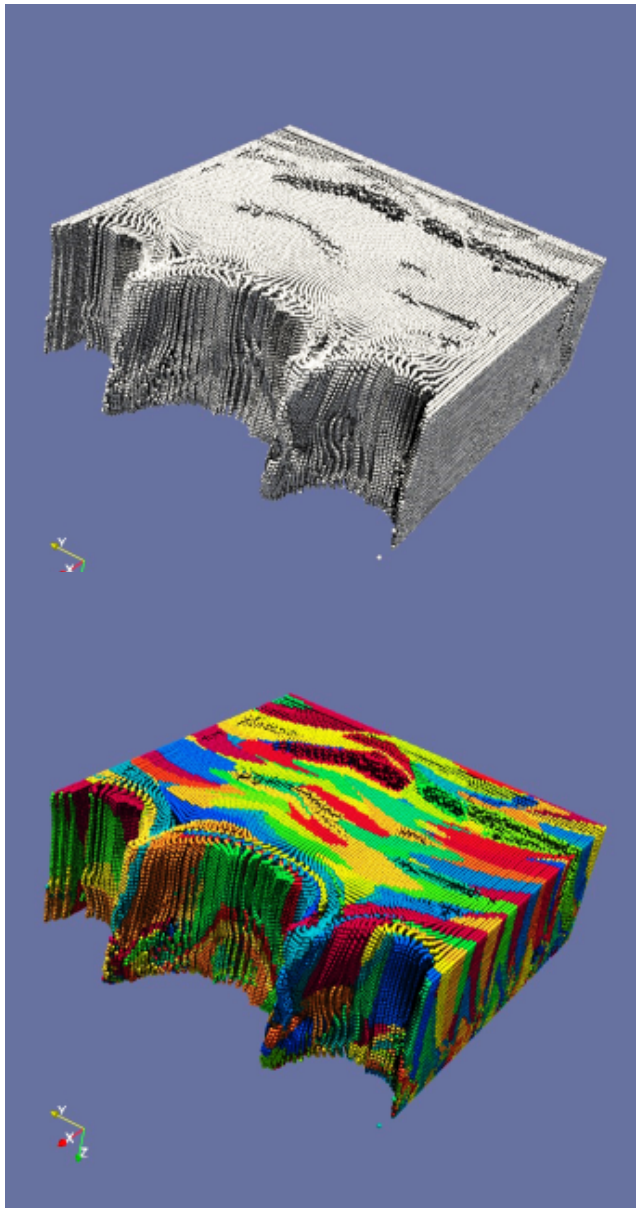


Wrought



1061 ns after impact





Microstructure influences jet shape!

Conclusions

- Phase contrast imaging enables the visualization of distinct jet behavior in RMI experiments that cannot be observed through traditional velocimetry techniques.
- Material properties such as surface tension, viscosity and strength effects can be probed in order to calibrate constitutive models.
  - Later time failure mechanisms can be accounted for in model using Peridynamics.
  - Microstructure does influence constitutive properties
  - Further our understanding of how microstructure for AM materials effects material behavior and properties.

Sandia National Laboratories

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