SAND2022-9206C

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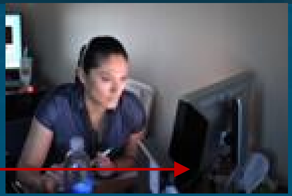
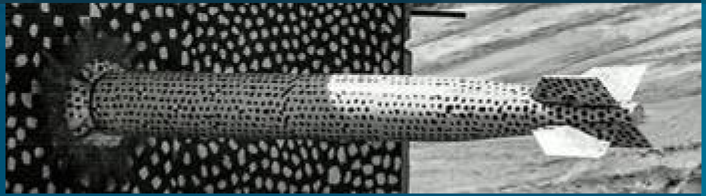
Peridynamic modeling of the dynamic failure of additively manufactured steel





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WCCM
Yokohama, Japan

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U.S. DEPARTMENT OF ENERGY NNSA

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Outline

- Spall phenomenology and testing.
- Peridynamics background.
- Crystal plasticity model.
- Spall kinetics model.
- Impact simulations and comparison with test data.

Motivation

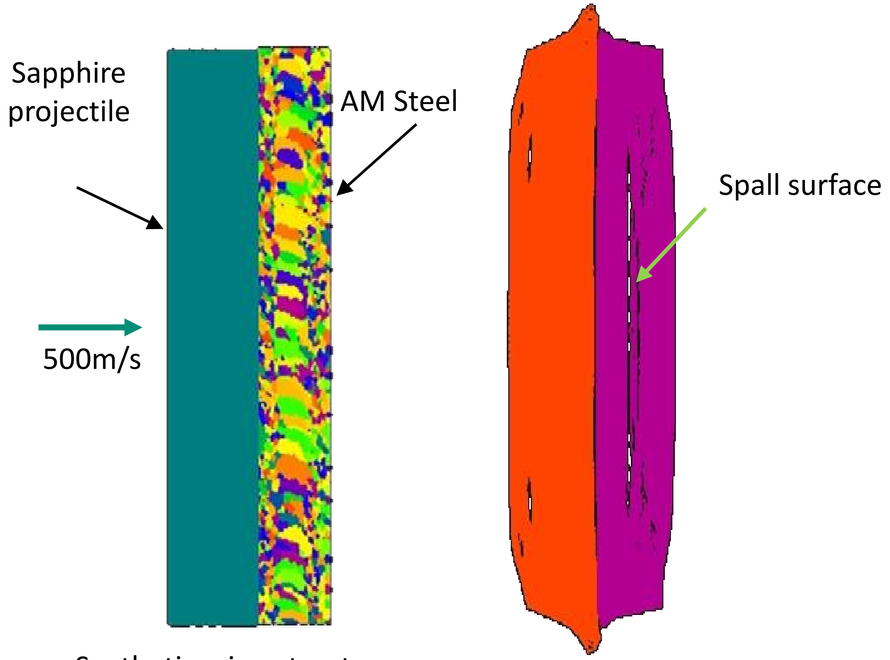
Can additively manufactured metals be substituted for conventional in applications involving shock waves?

Acknowledgments

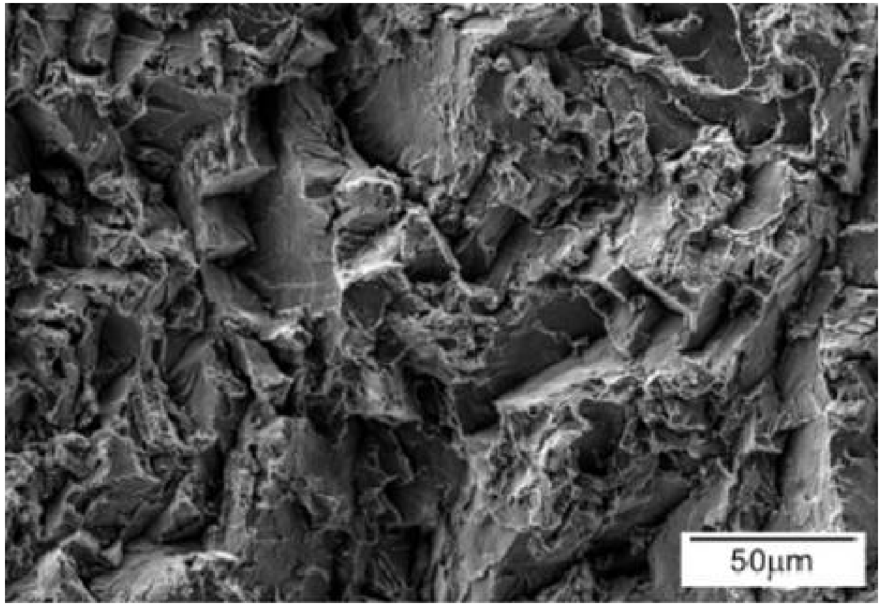
Justin Brown, Nathan Brown, John Mitchell, Tim Ruggles, Paul Specht

Failure of metals under impact loading

- Plate impact experiments are used in various configurations to measure dynamic material properties.
  - Equation of state data (Hugoniot and release).
  - Dynamic strength under high-rate tensile loading (~ 10^5 1/s)
  - Spall stress >> quasi-static tensile strength (typically > 3GPa for steel).
- Basic test data is the free surface velocity.



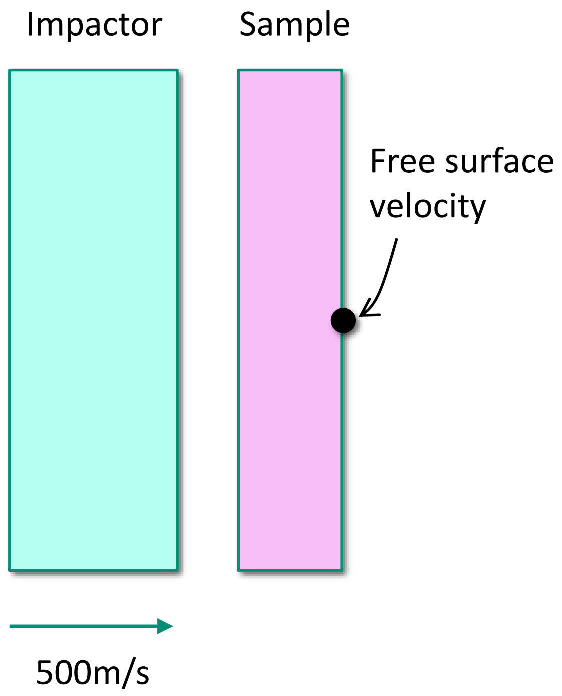
Synthetic microstructure

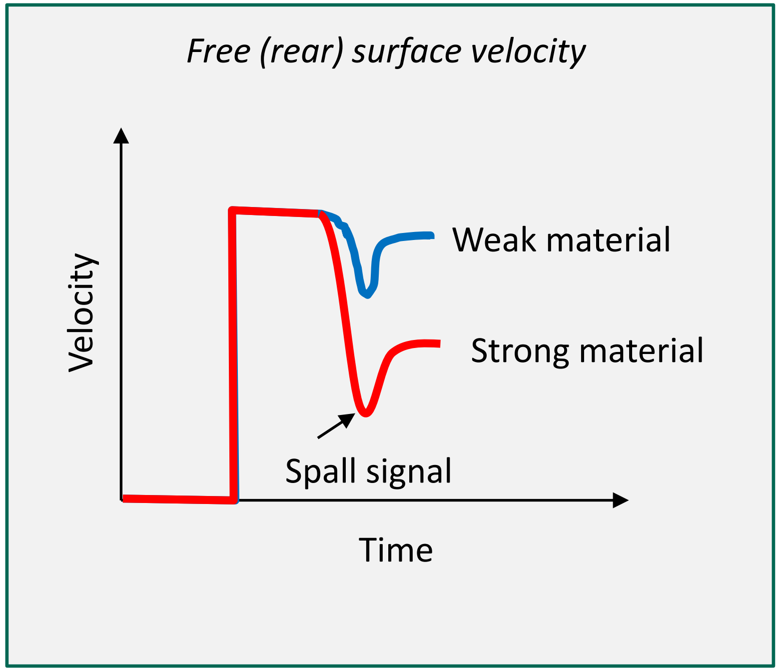


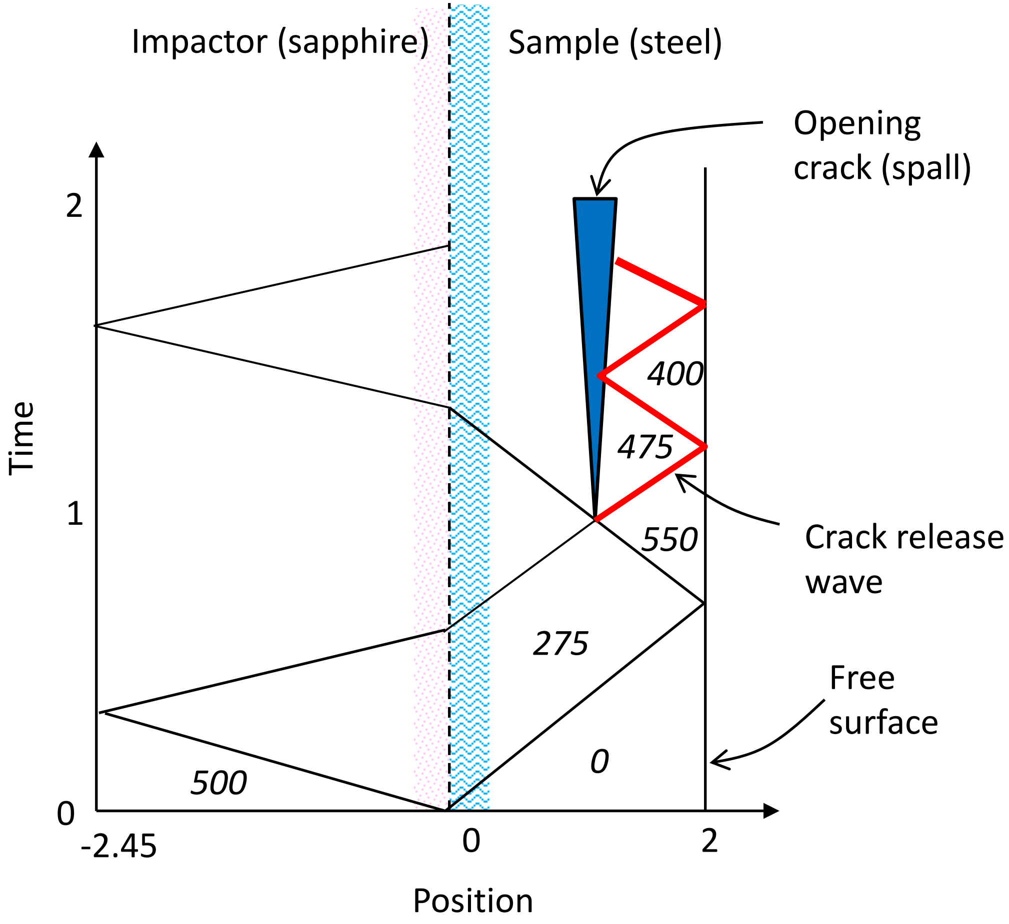
Spall surfaces can be irregular*

*Image: E. Svabenska et al., "Effect of shock wave on microstructure of silicon steel", Surfaces & Interfaces (2020).

Wave reflections lead to strong tension





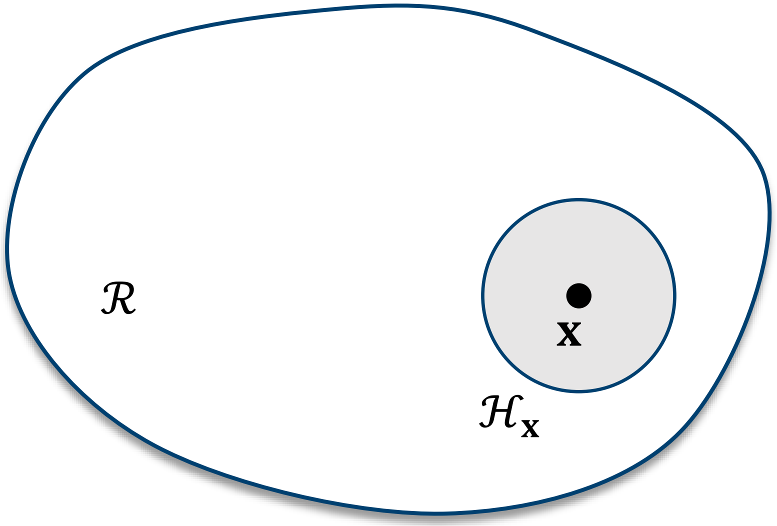


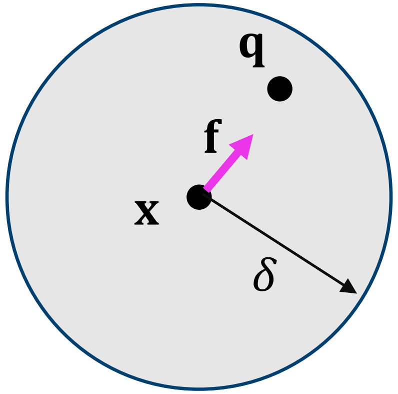
Peridynamics background

- Peridynamic momentum balance in 3D:

$$\rho(\mathbf{x})\ddot{\mathbf{u}}(\mathbf{x},t) = \int_{\mathcal{H}_\mathbf{x}} \mathbf{f}(\mathbf{q},\mathbf{x},t)\, d\mathbf{q} + \mathbf{b}(\mathbf{x},t) \qquad \forall \mathbf{x} \in \mathcal{R},\ t \geq 0.$$

- $\mathbf{f}$ is the *pairwise bond force density* of the *bond* from $\mathbf{q}$ to $\mathbf{x}$.
- $\mathcal{H}_\mathbf{x}$ is the *family* of $\mathbf{x}$, which is a ball centered at $\mathbf{x}$ with radius δ (the *horizon*).

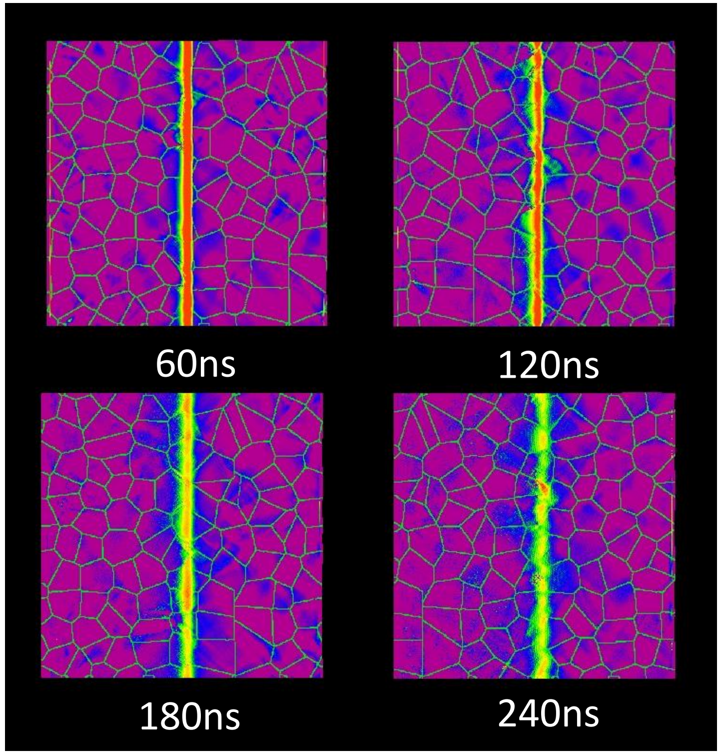




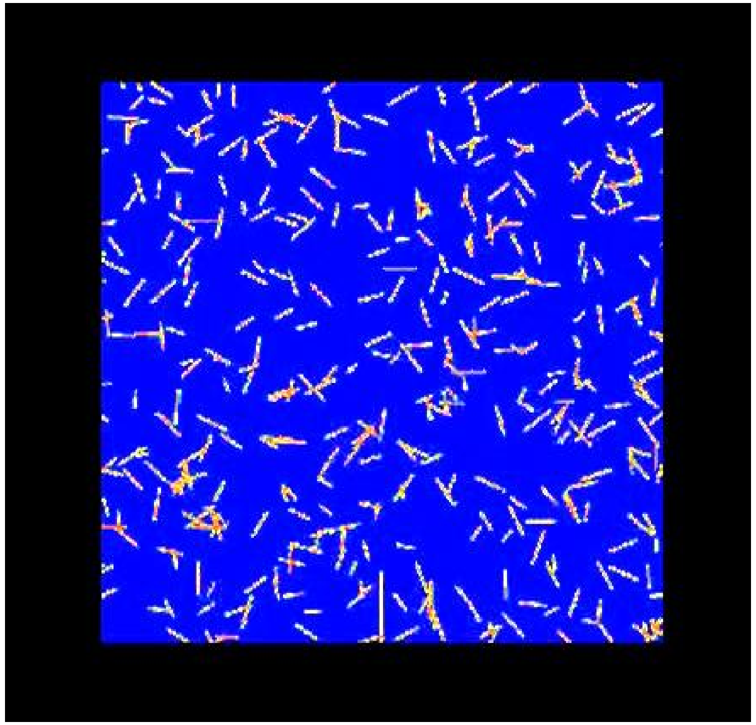
Peridynamics allows fractures to appear spontaneously

- Integral equations: no need to try to differentiate on a singularity.
- Meshless discretization allows grains to be defined in any shape without a FE mesh.
- Bonds fail according to a damage criterion..
  - which in this case is supplied by the Spall Kinetics Model (more later).

Example of shock wave propagation
Colors show strain rate



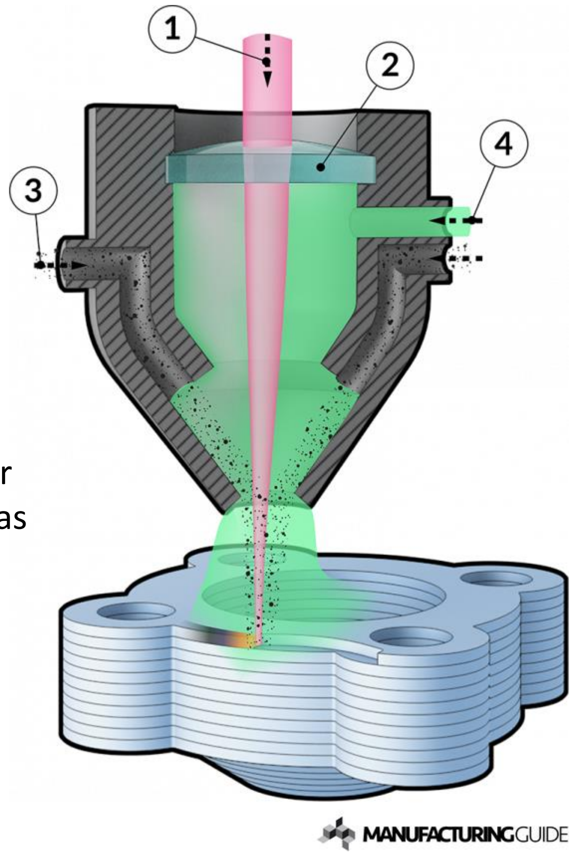
Example of macroscopic failure in a sample with defects
VIDEO



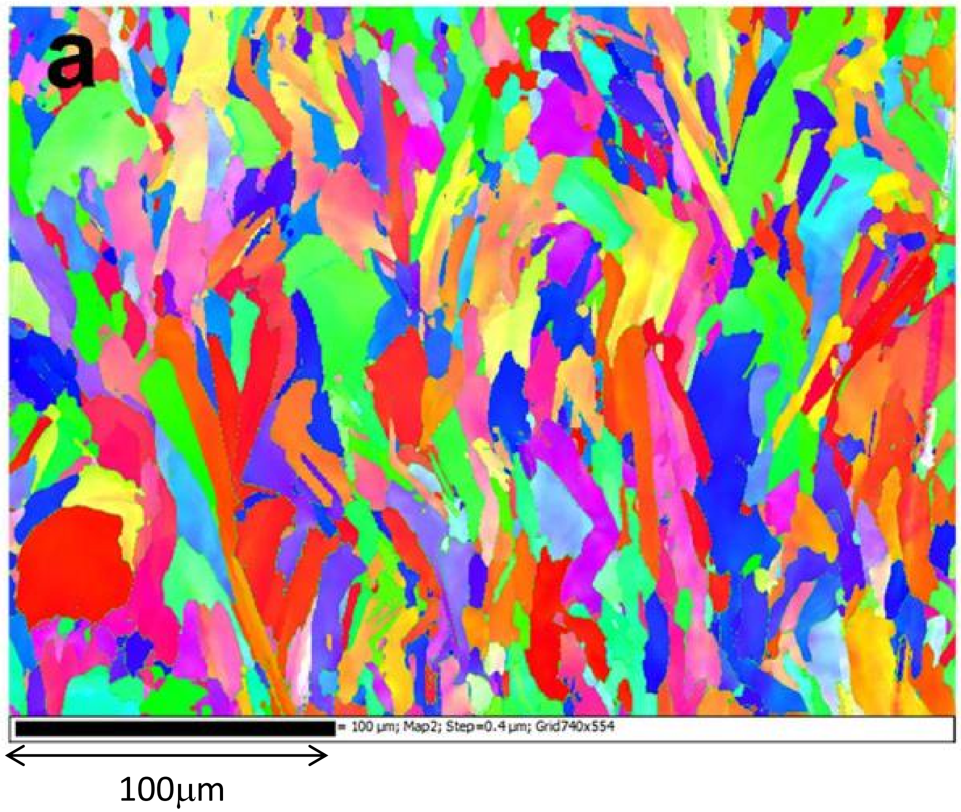
LENS process

- Large, elongated grains are typically formed
- Nonuniform thermal history

1. Laser
2. Lens
3. Powder
4. Inert gas



Typical microstructure



Images:
- https://www.manufacturingguide.com/en/laser-engineered-net-shaping-lens-0
- S. Gorsse et al, *Science and Technology of Advanced Materials* (2017)

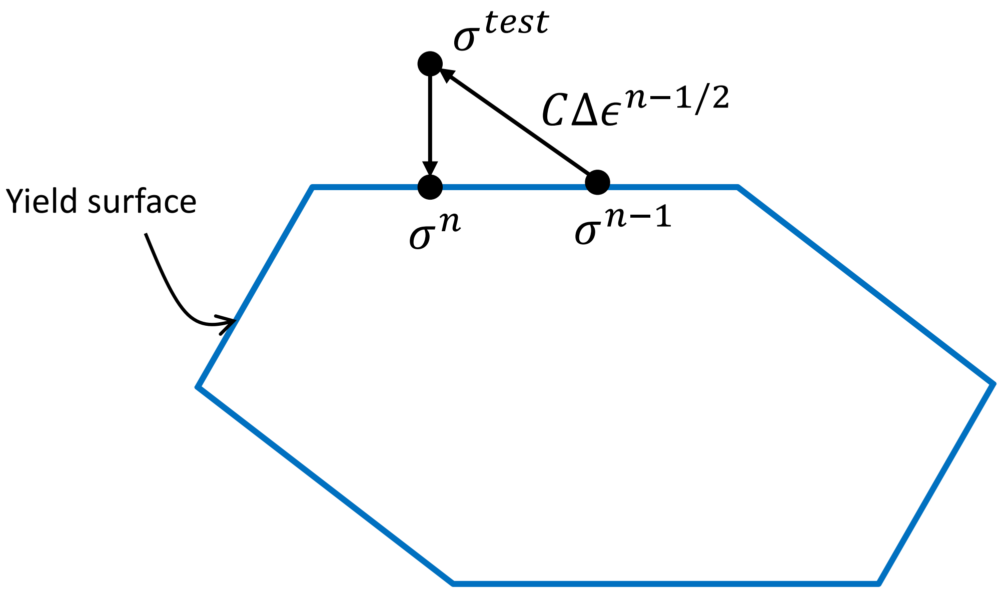
Crystal plasticity model*

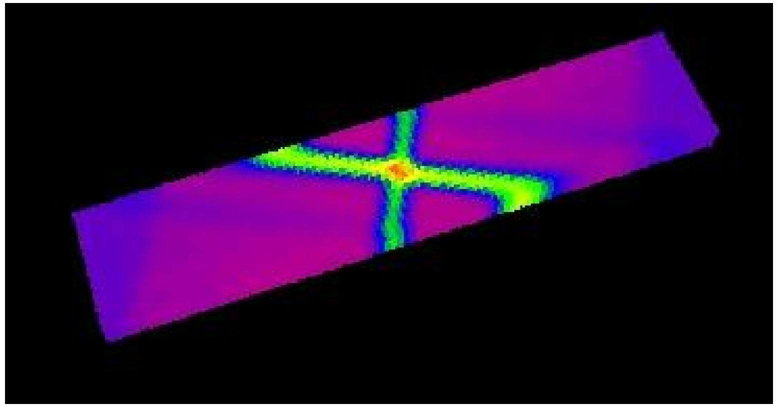
- Analogous to the radial return method
- The slip systems limit the deviatoric stress to a polyhedron in the space of deviatoric tensors.
- A test stress is found from the previous cycle stress and the current stress increment.

$$\sigma^{test} = \sigma^{n-1} + C\Delta\epsilon^{n-1/2}$$

where C is the anisotropic 4th order elasticity tensor.

- The new stress σ^n is the point on the surface closest to the test stress.



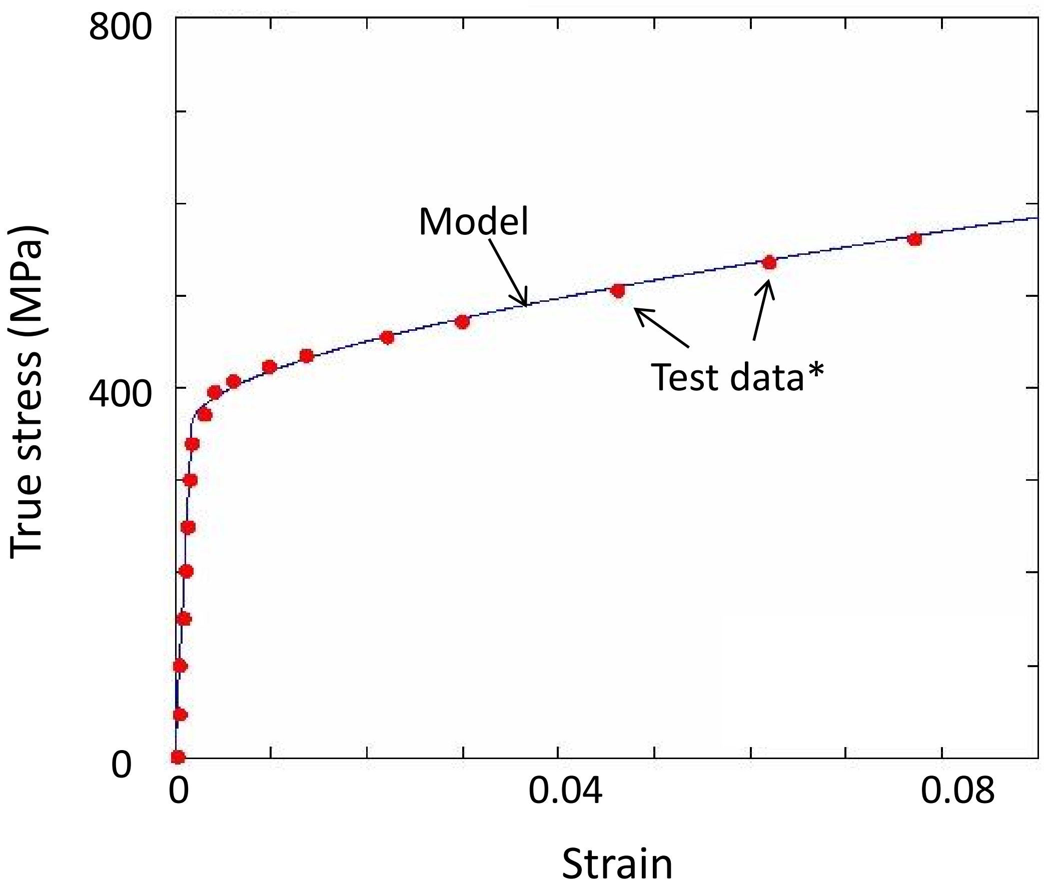


Stretching of a bar with one slip system
Colors show equivalent plastic strain

* P. Maudlin and S. Schiferl, *Computer Methods in Applied Mechanics and Engineering* (1996)

Fit to quasi-static stress-strain data for AM 304L stainless steel

- Sample was additively manufactured with the Laser Engineered Net Shaping (LENS) process.
- The model also contains temperature and strain rate dependence.

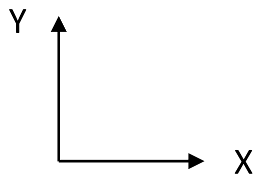


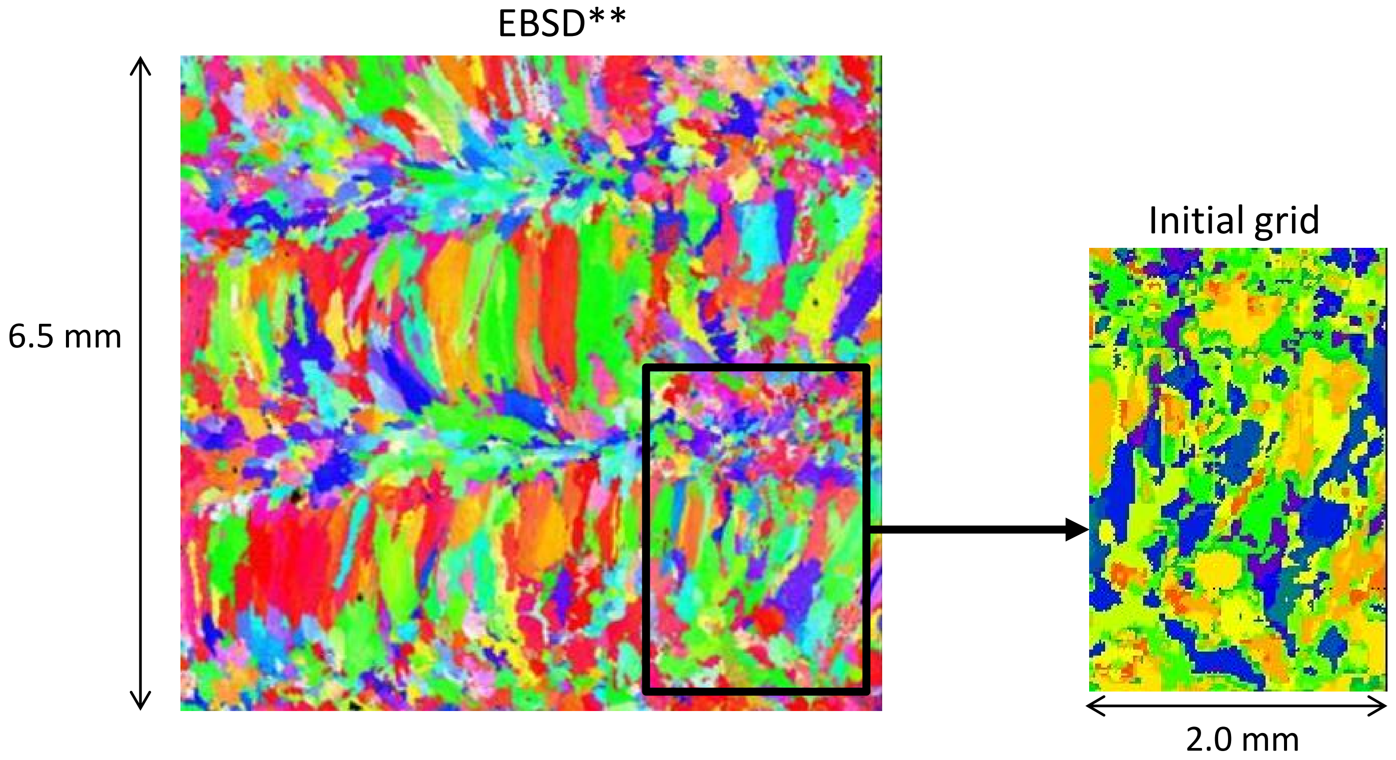
* D. P. Adams et al., Sandia tech report SAND2019-7001 (2019)

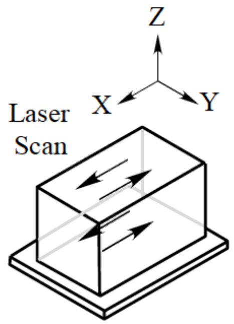
Assignment of lattice orientations

- Grains are imported into the model from electron backscatter diffraction (EBSD) images.
- Lattice orientations are assigned randomly using Euler angles.
- These are combined with published anisotropic crystal elasticity data* for 304L SS to compute C for each grain.

$$C_{11} = 209\text{GPa} \qquad C_{12} = 133\text{GPa} \qquad C_{44} = 121\text{GPa}$$



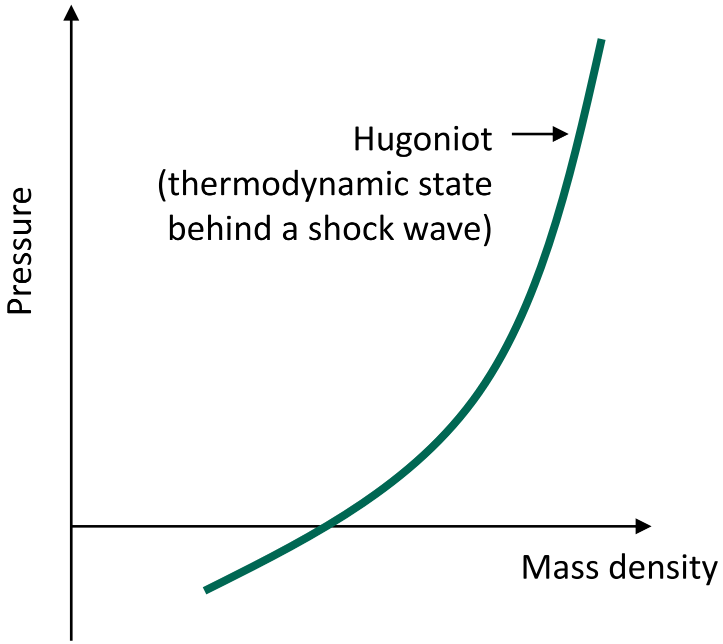


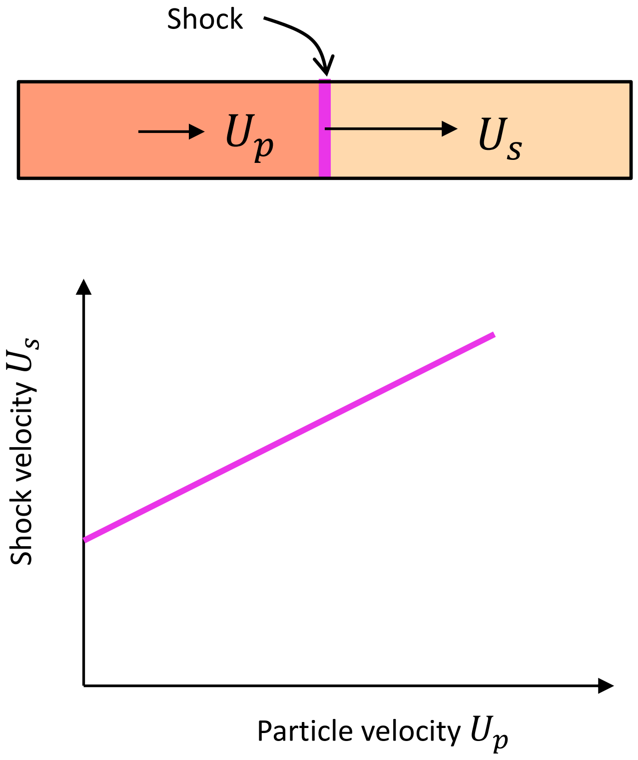


*H. Ledbetter, Physica B+C (1985)
**Image: T. Ruggles

Equation of state

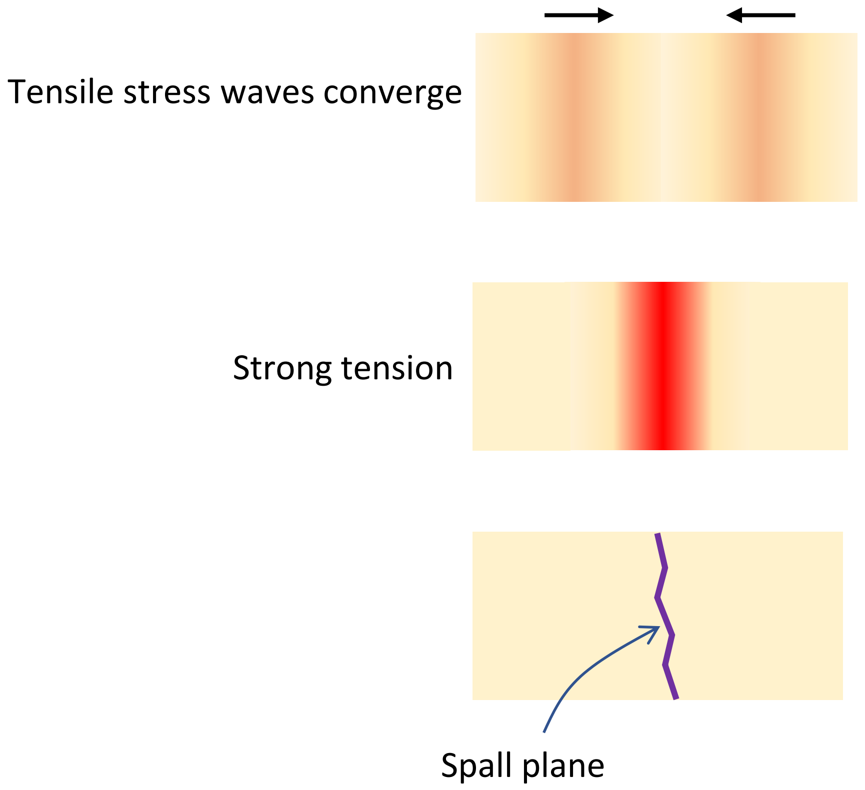
- Add a pressure term to the deviatoric stress found from the crystal plasticity model.
- Mie-Gruneisen EOS:
    - Input: Internal energy density, mass density
    - Output: Pressure, temperature
    - Shock velocity is a linear function of particle velocity behind the shock.
    - Same EOS for all grains

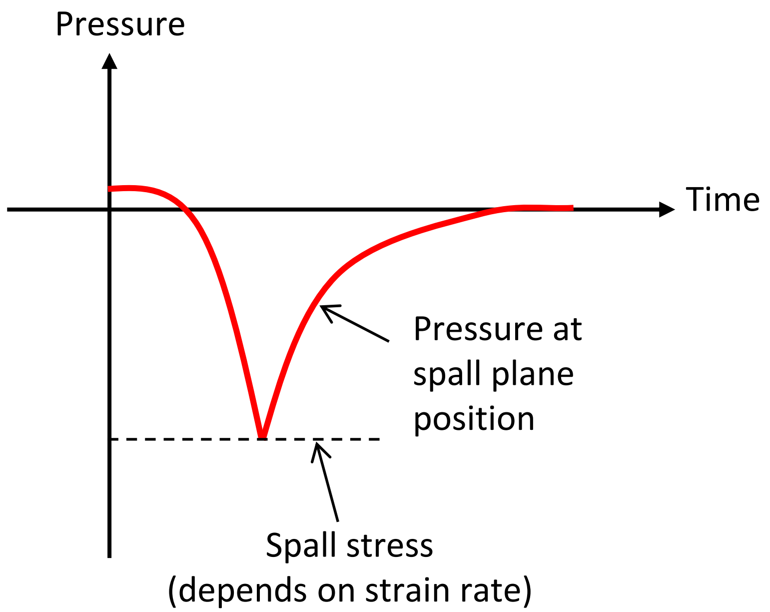




Spall kinetics model

- Failure occurs over a finite period of time.
- The rate of failure depends on the peak tensile stress and strain rate.

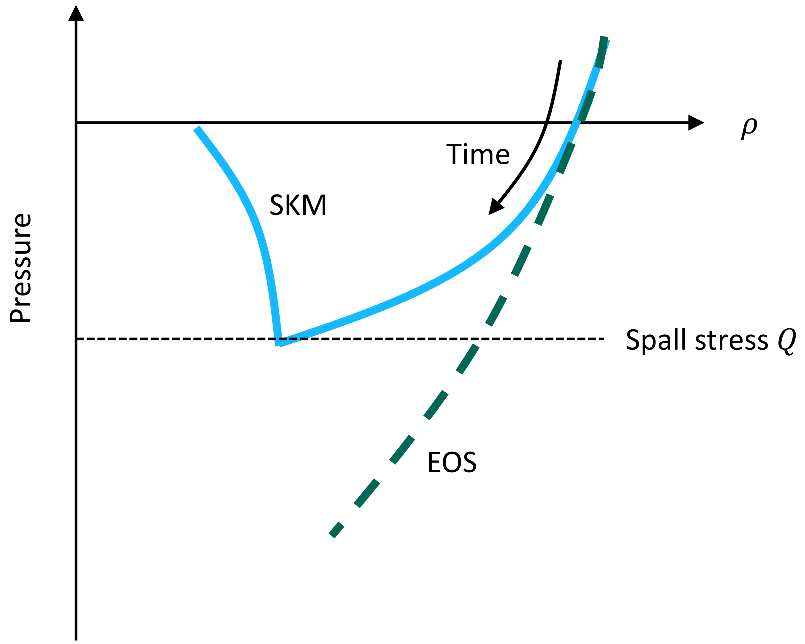




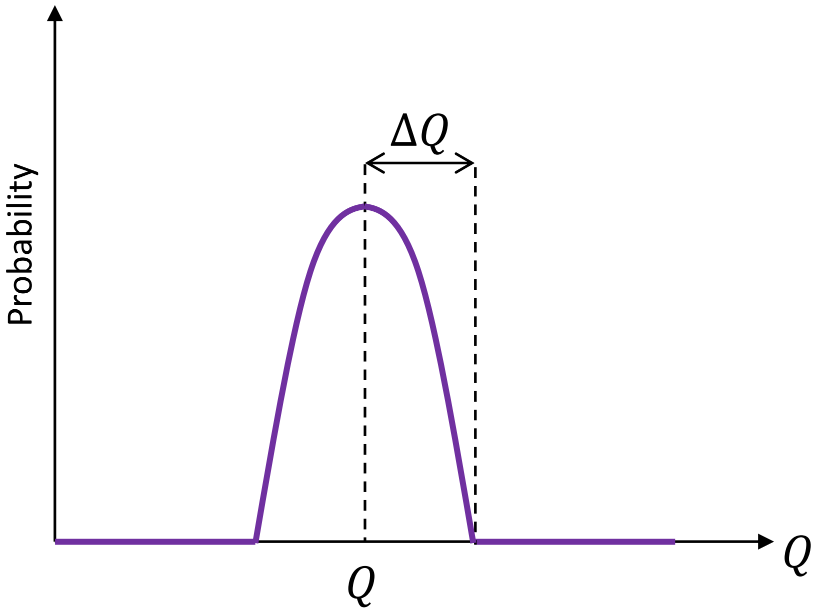
Spall kinetics model: softening and variability

- The EOS is modified to include softening as the critical stress for failure is approached.
- Each grain (from EBSD) is randomly assigned a value of spall stress.

Softening and failure during expansion

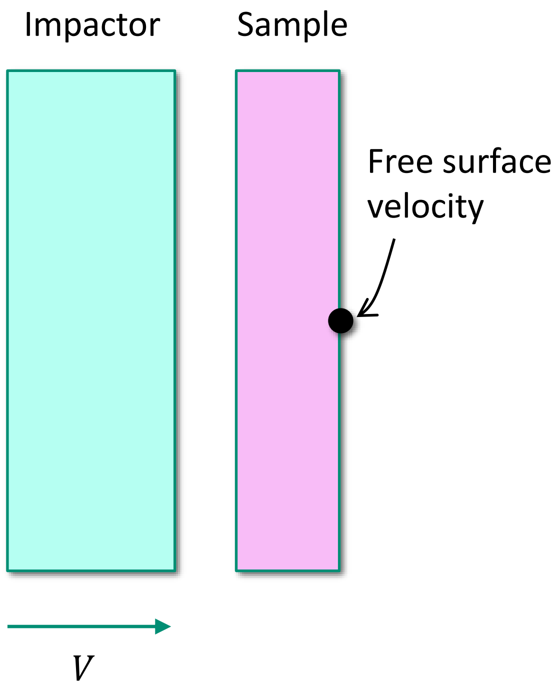


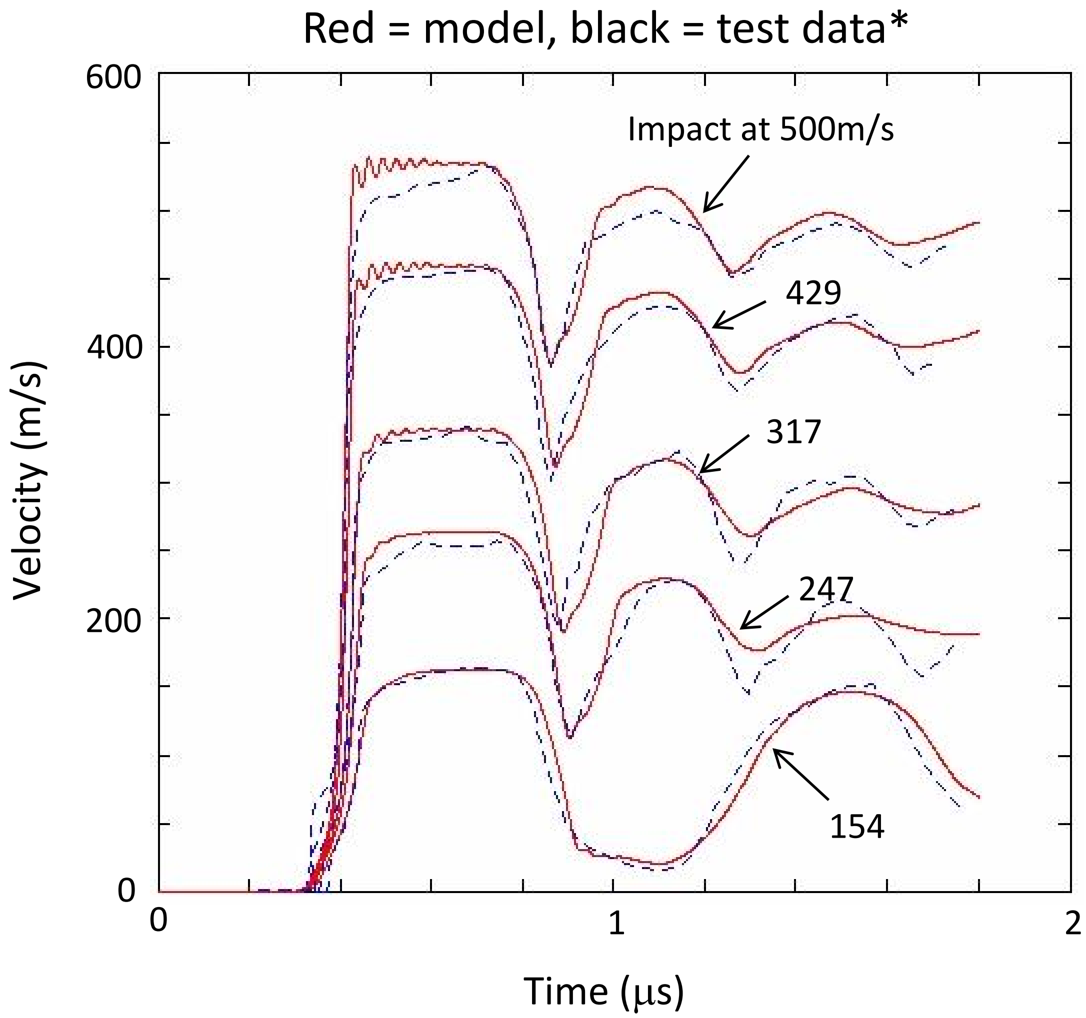
Grain-to-grain variability in spall stress



Results: Free surface velocity

- Figure compares model results with test data.



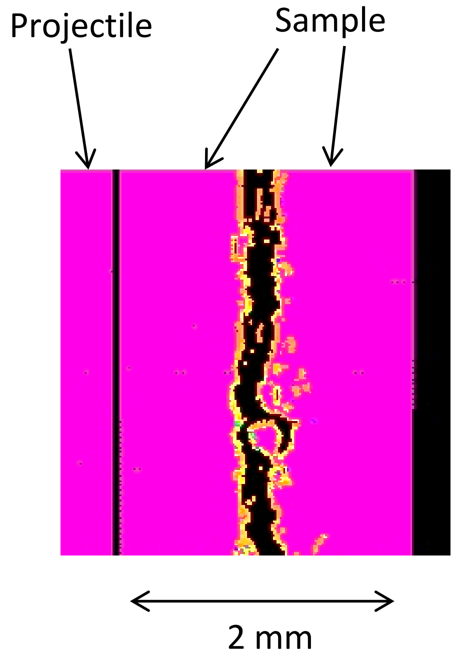


* J. L. Wise et al., AIP Conference Proceedings (2017)
P. E. Specht et al., Sandia tech report SAND2019-12275 (2019)

Spall surface condition

$V = 317\mathrm{m/s}$

Experiment*

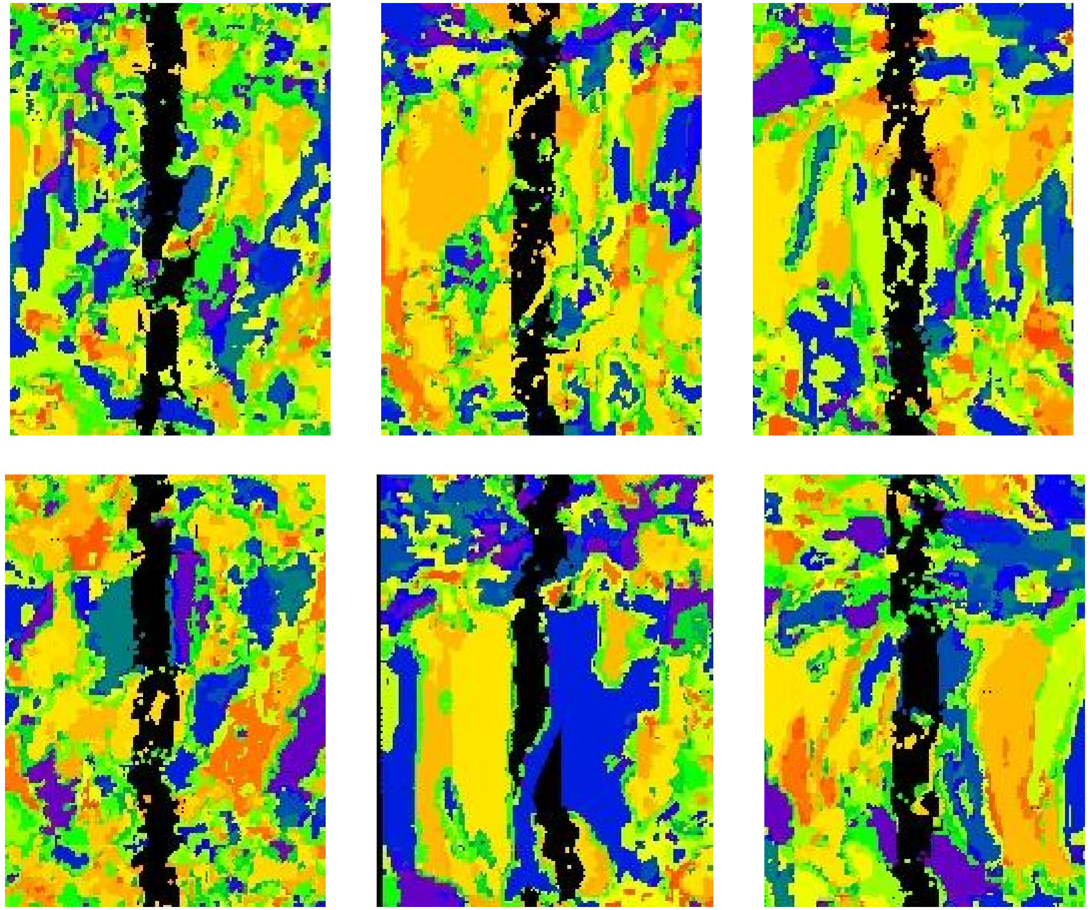


Model
(Colors show damage)

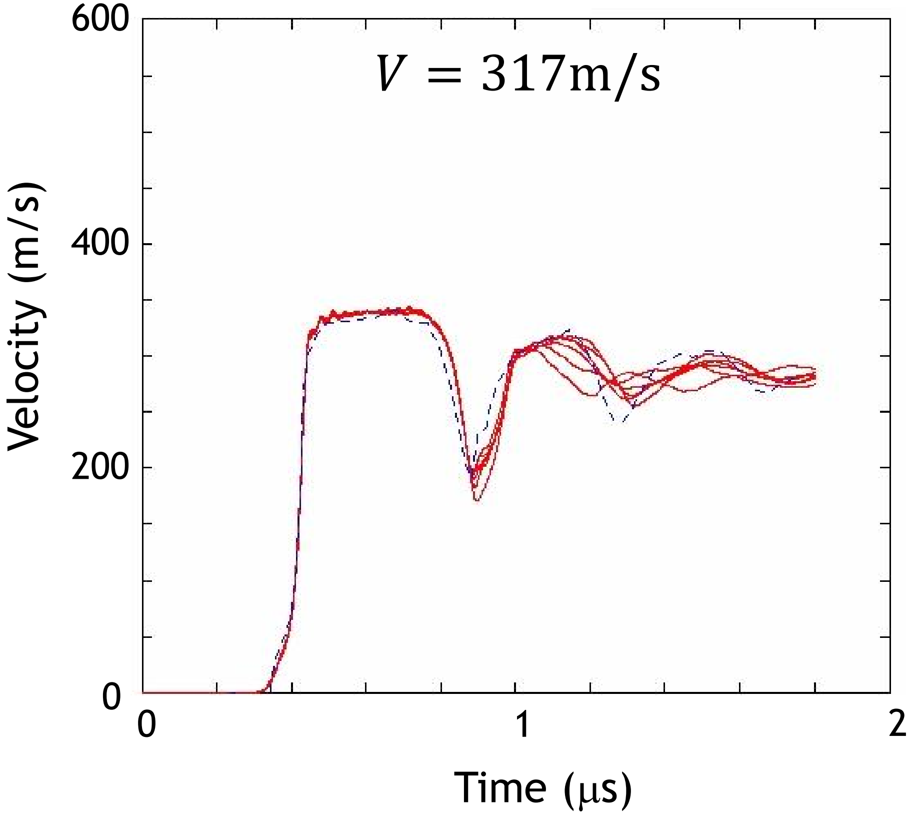
* D. P. Adams et al., Sandia tech report SAND2019-7001 (2019)

Effect of microstructure

- What is the effect of extracting different samples from within the EBSD image?
- Makes some difference at intermediate impact velocities.



Free surface velocity for the 6 samples, all X-cut



Discussion

- The large and distorted grain shapes with AM materials affect the dynamic failure properties.
- A number of new capabilities have been implemented in peridynamics:
  - Crystal plasticity
  - Importing microstructures
  - Spall kinetics model
  - Material variability
- The resulting model reproduces the main features of the test data over a range of impact velocities.

This work: S. Silling, D. Adams, and B. Branch, "Mesoscale Model for Spall in Additively Manufactured 304L Stainless Steel", to appear *in Intl J Multiscale Computational Engineering* (2022)