SAND2015-7016C

Mechanical Response of Additively Manufactured (AM) Stainless Steel 304L across a Wide Range of Strain Rates

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Solid Freeform Fabrication (SFF) 2015
Austin, Texas

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Motivation and Approach

- Desire improved understanding of high strain rate response (to $\dot{\varepsilon}$ ~ 1e7 s^{-1}) and variability.
- Evaluate the roles of phase, structure, composition.
- Use baseline measurements of structure, mechanical properties to build predictive models of deformation starting with quasi-static regime.

For progress on predictive modeling, see presentations today by

Reedlunn 10:45 Modeling III

Bishop, Poster session

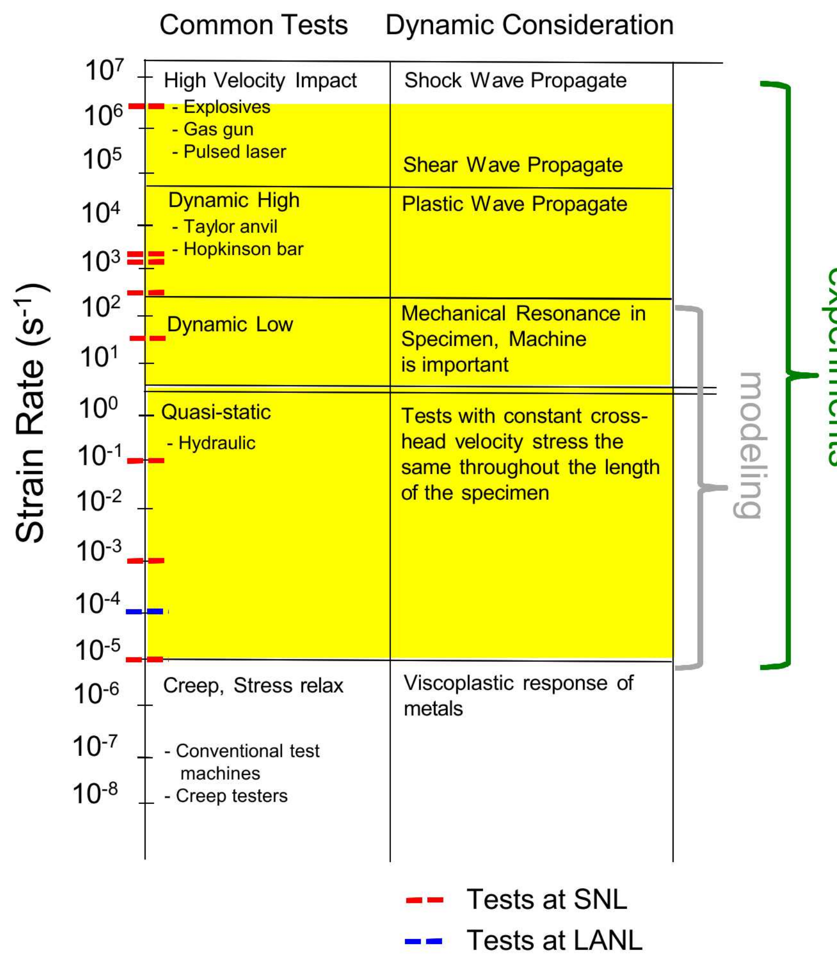


Chart is from Meyers' Dynamic Behavior of Materials

Additive Manufacturing Processes used in this Study

- Three forms of AM Material

  P_{avg} = 3.8 kW, 2.0 kW, 500 W (first two use a 4 mm spot)

- Relevant rates (for those interested in processing)

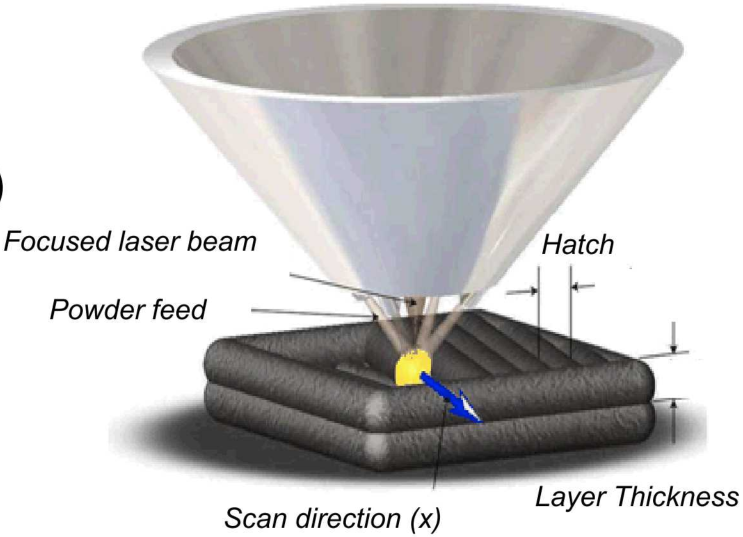
  P_{avg} = 500 W : 15 g/min, 15 ipm, 0.5 mm/layer

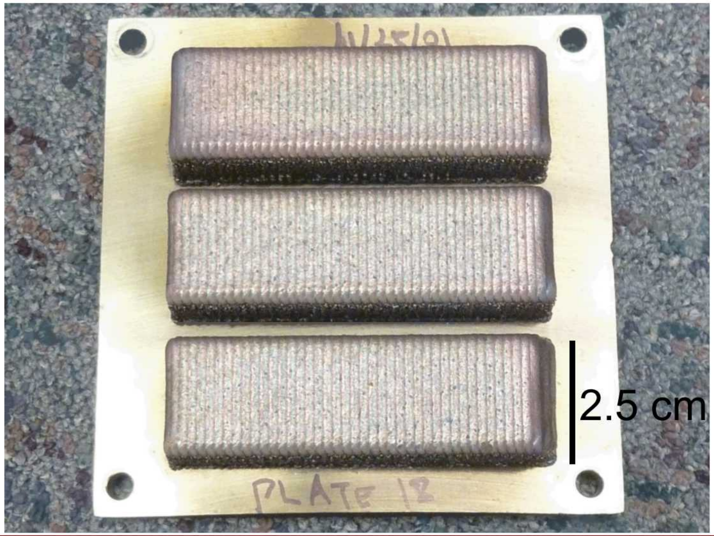
  P_{avg} = 2.0 kW : 20 g/min, 20 ipm, 0.89 mm/layer

  P_{avg} = 3.8 kW : 23 g/min, 25 ipm, 1.25 mm/layer

- Micromelt 304L powder (Carpenter Powder Products)

- Parallel build processes and cross hatch





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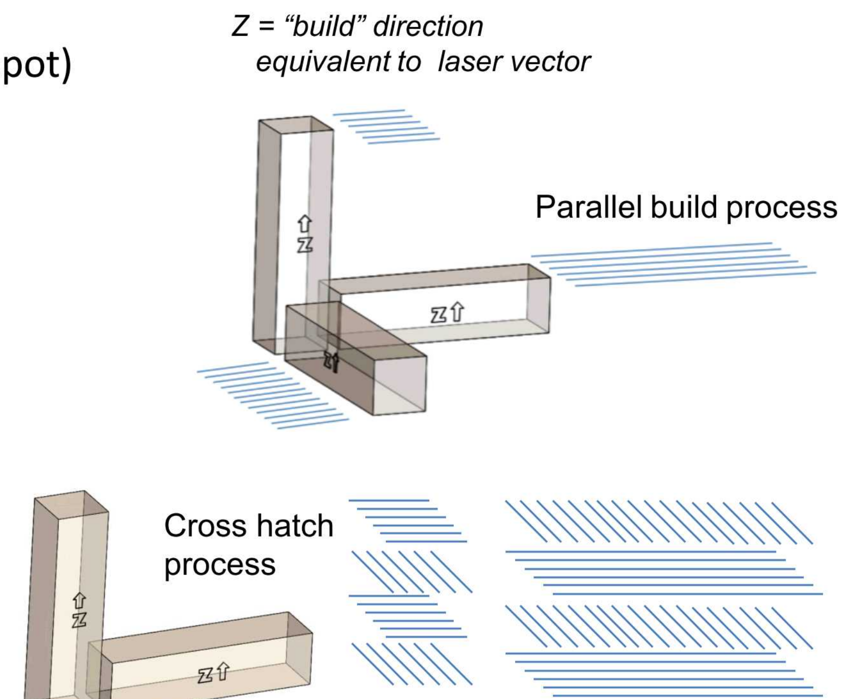
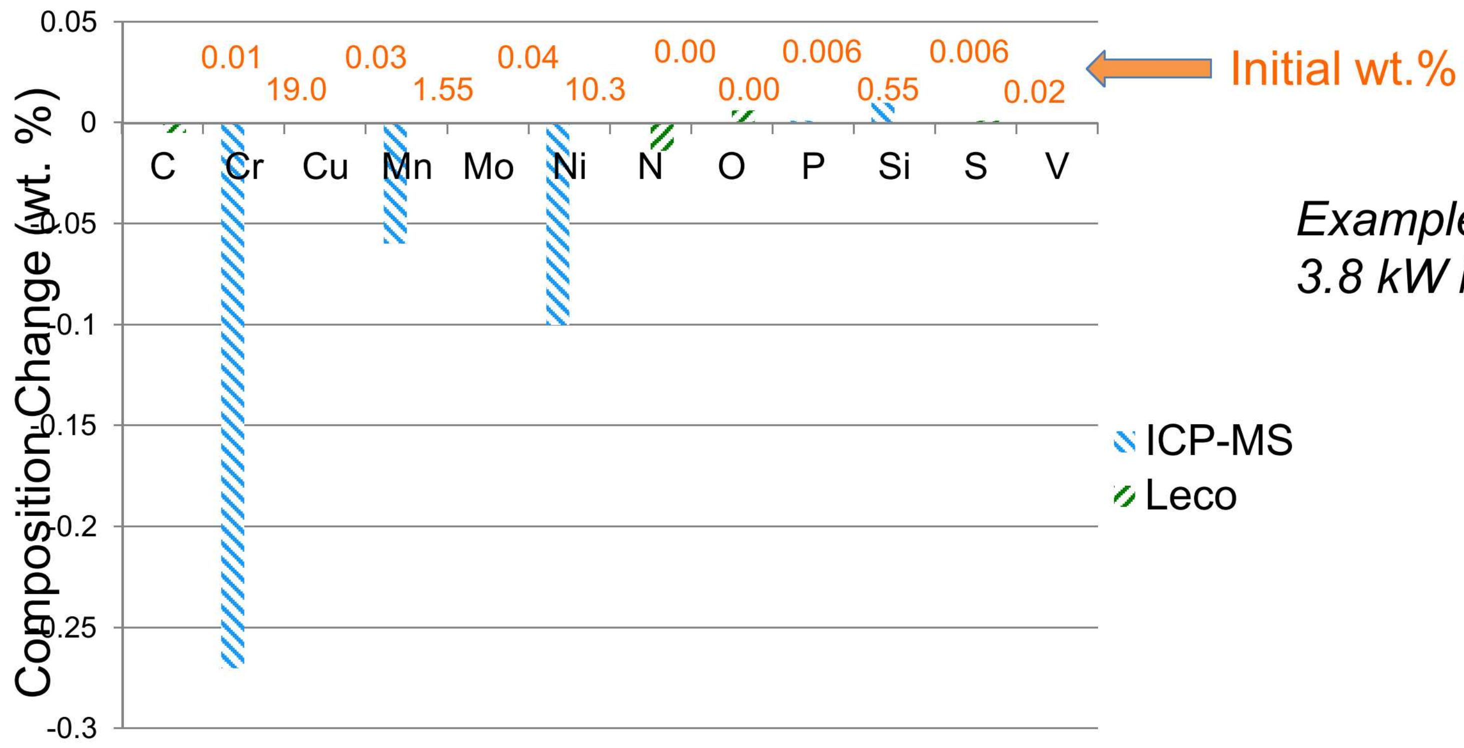


Schematic raster fill patterns

Sample Geometry

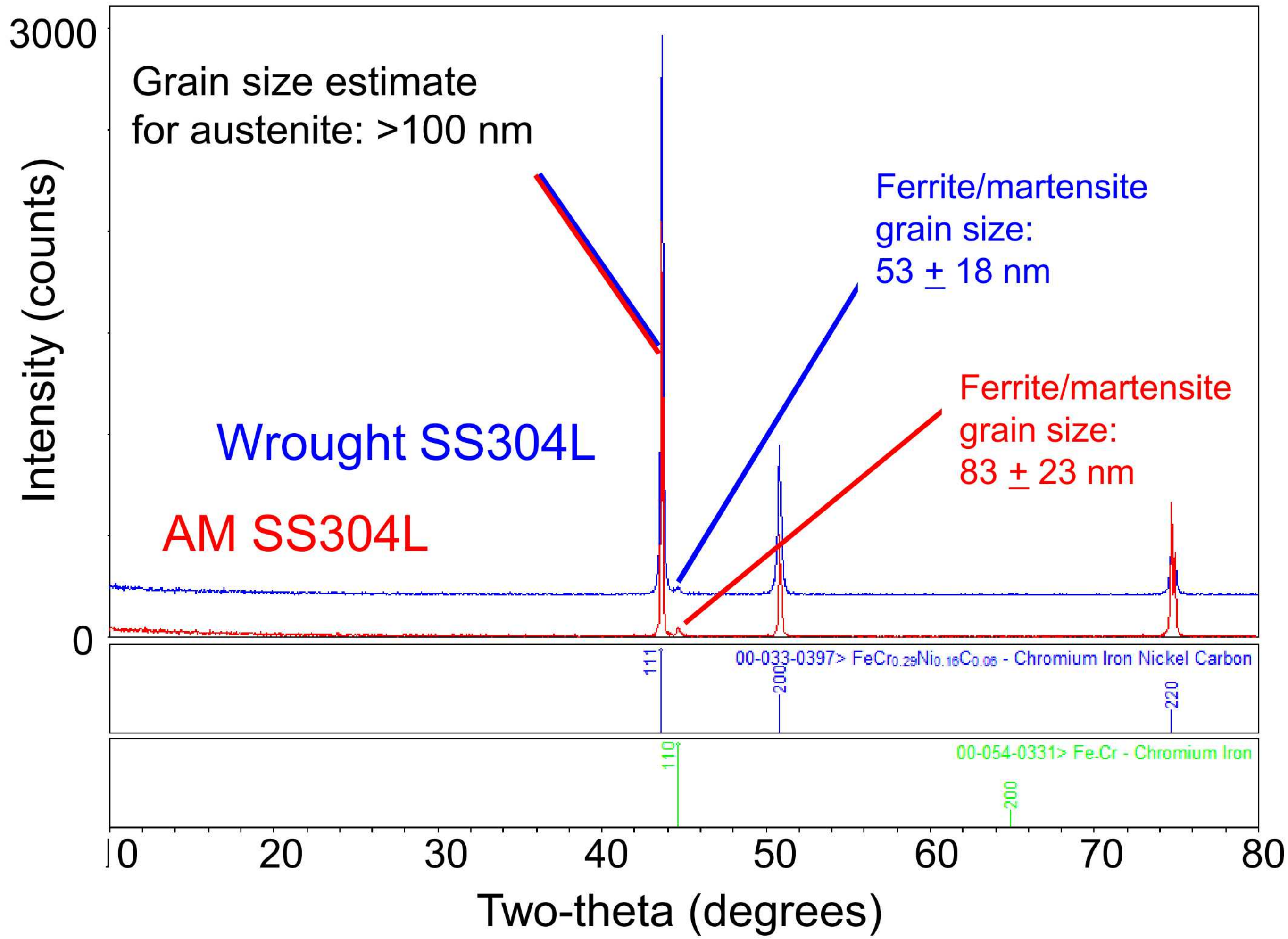
The composition of the AM material changes slightly, suggests vaporization.



Example is for a 3.8 kW bar

Results are referenced directly to measured composition of starting 50-100 μm powder from Carpenter Powder Products.

Phase of AM Material has been characterized.

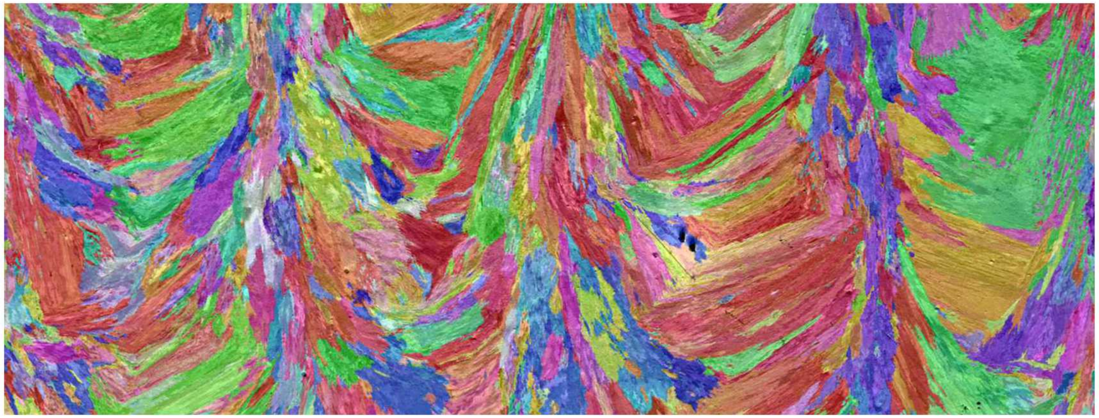


Each form has approximately 1-2% ferrite (verified by Ferritescope)

Large area views of microstructure of AM SS304L (3.8 kW)

- Electron backscatter diffraction maps of electropolished surfaces.
- Example shown was built with parallel scan approach.
- Density has been confirmed at 99.85% FTD (Archimedes).

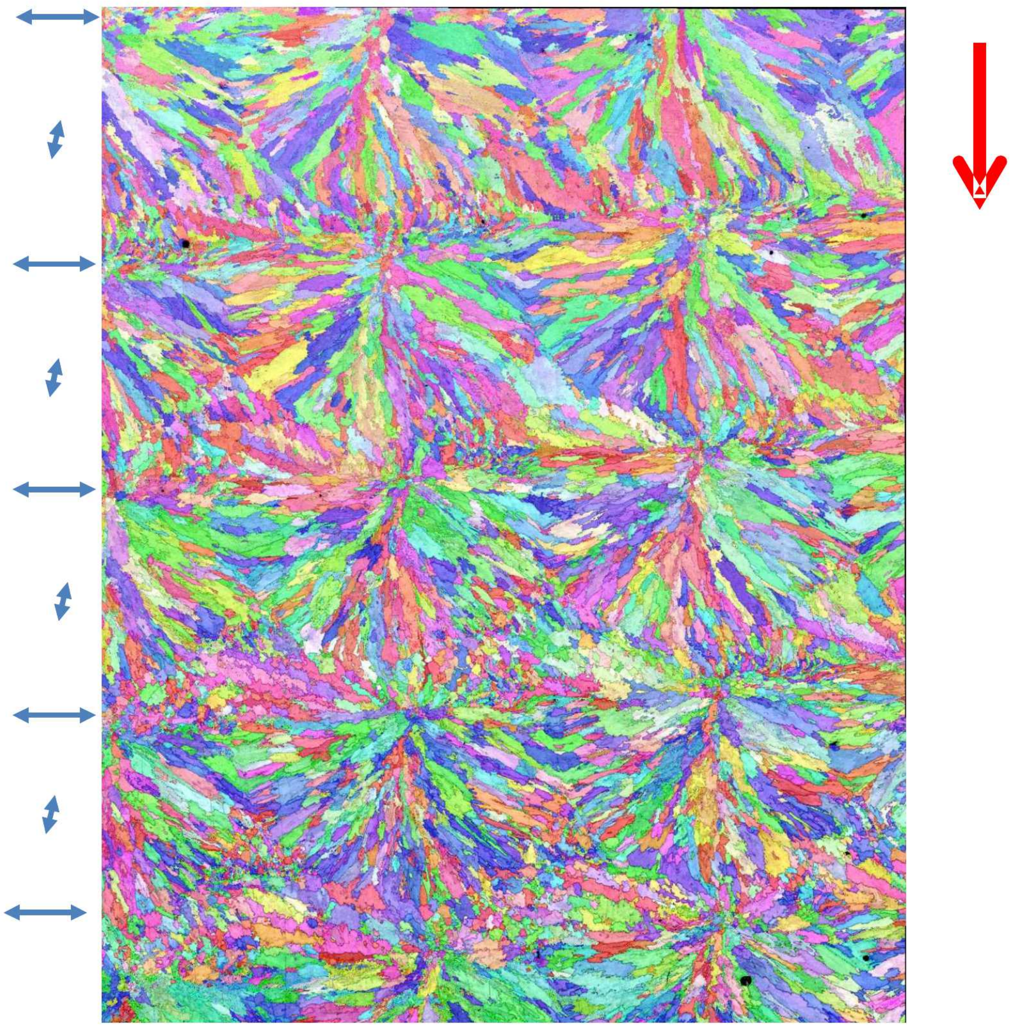
For a more detailed understanding of this material's crystallographic texture (before, during and after deformation) see presentation today by Ben Reedlunn (Modeling III @ 10:45)



x projection, approx 4 x 8 mm

Large area views of microstructure of AM SS304L (2.0 kW)

- Electron backscatter diffraction maps of electropolished surface.
- Example shown to write was built with a cross hatch approach.
- Density has been confirmed at 99.8% FTD (Archimedes method).

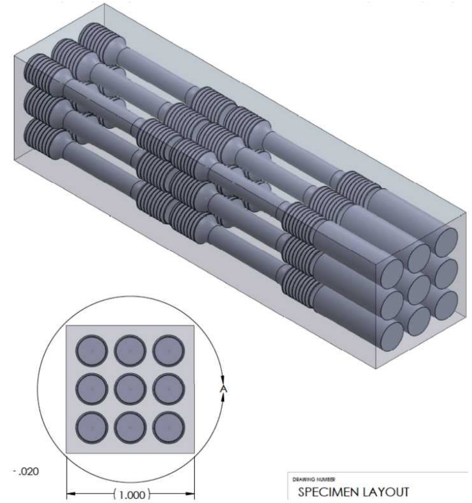


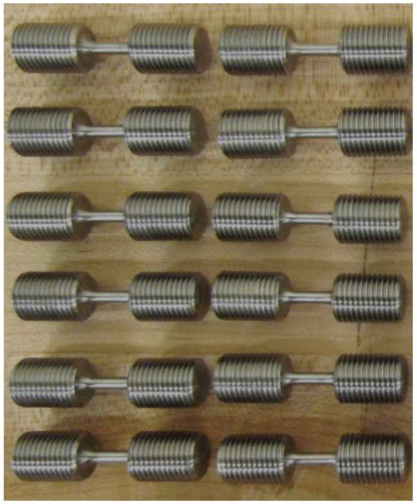
6 mm wide by 10 mm high

IPF X +BC

Preparation of Mechanical Test Samples

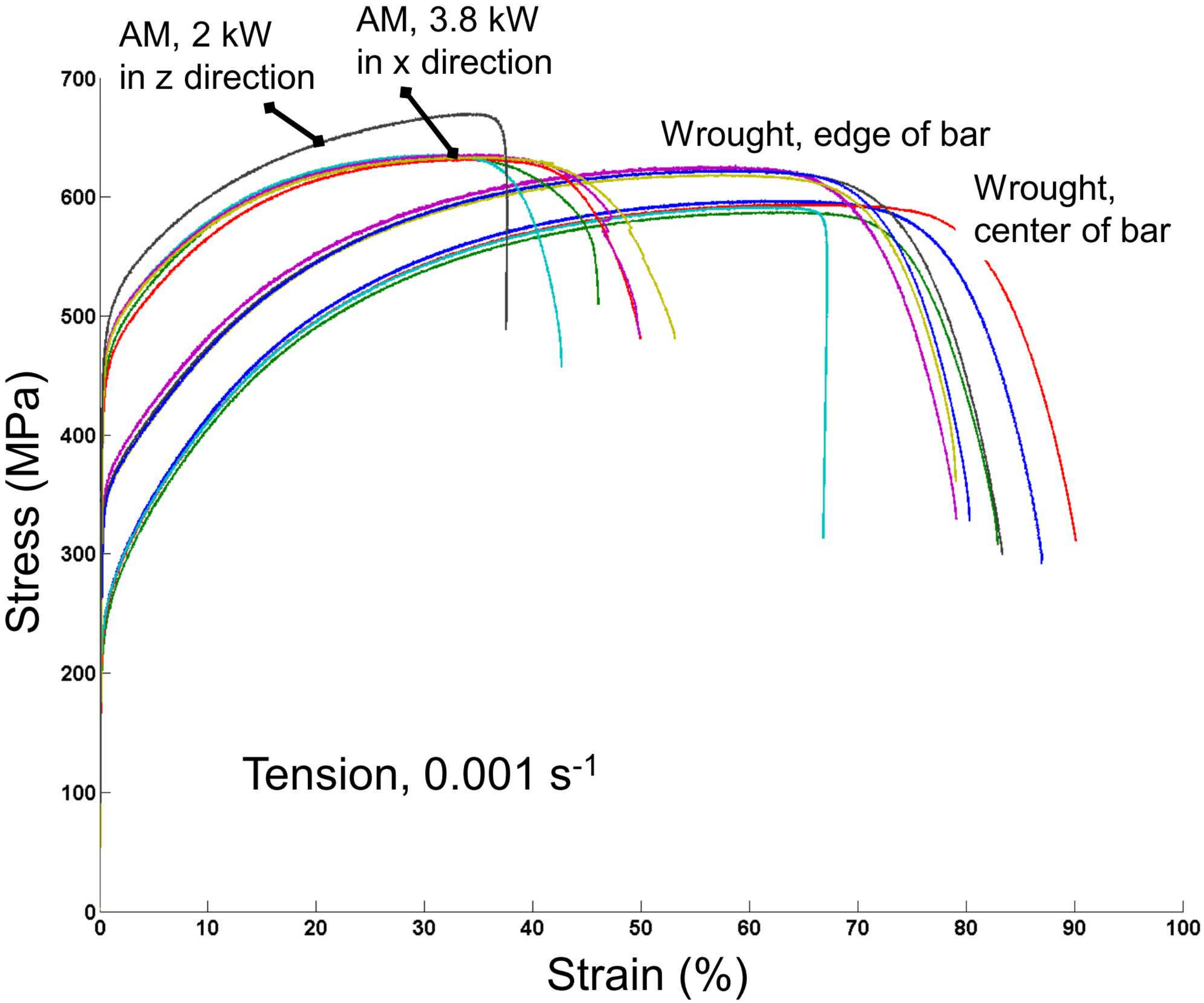
- Side by side comparison with wrought SS304L
- Compression and tension samples
- ASTM geometries chosen, when possible
- Edges of AM bars avoided
- Test samples removed by wire EDM, then machined
- Tests probe variability from within one bar





Altogether approx. 1000 mechanical tests are planned (with many completed) to research variability.

Quasi-static tests to failure show differences in high power AM vs. wrought.

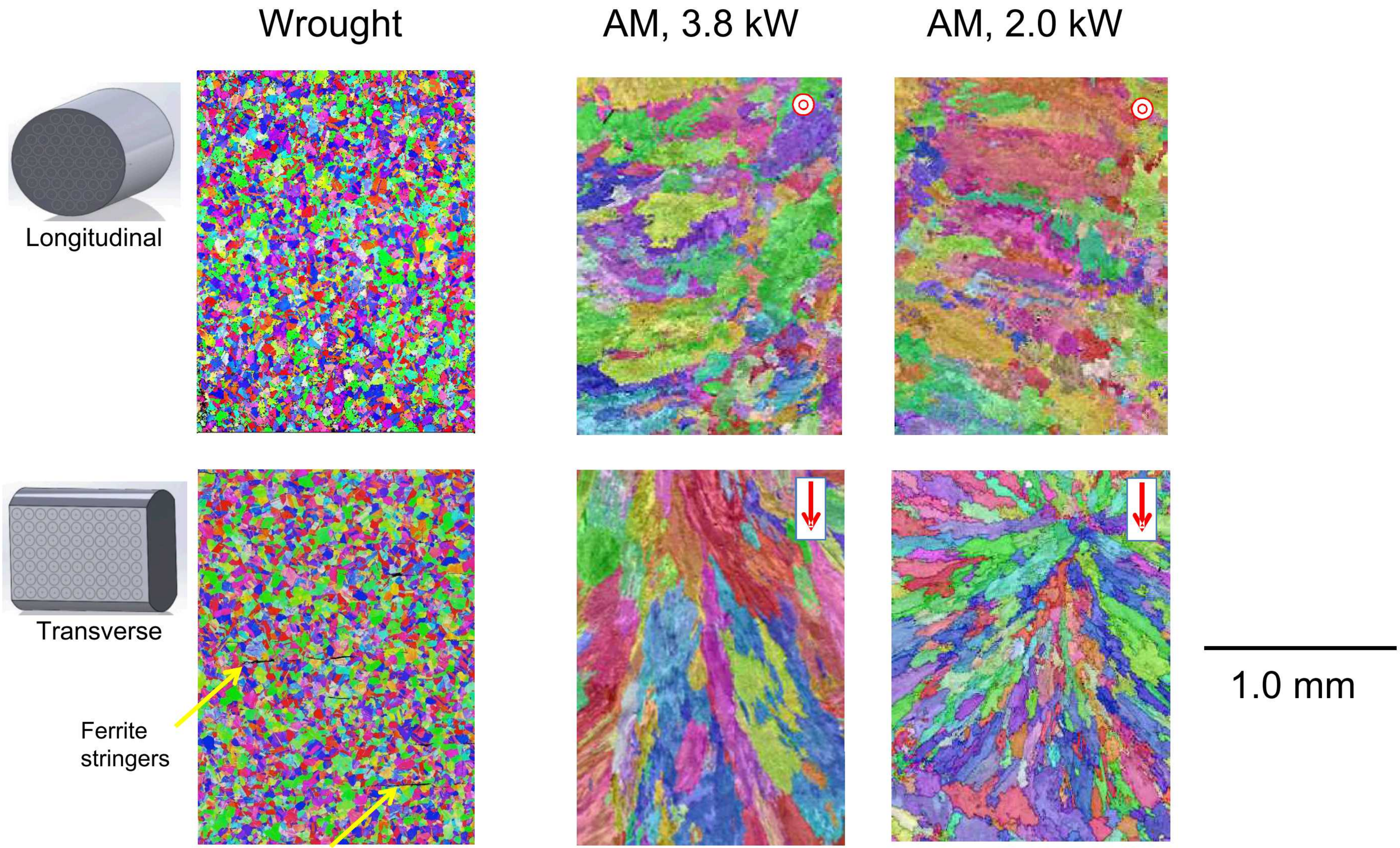


AM material behaves much like laser welded 304L SS (acknowledge Jeff Rodelas, SNL, for conversations).

Higher yield stress could be due to
- grain size differences X
- fine dispersion of ferrite
- small substructure (dendritic cells)
- oxide dispersions

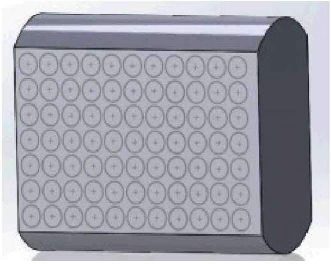
We are also evaluating the effects of residual stress by testing additional samples after heat treating.

Microstructure of Different Material Forms

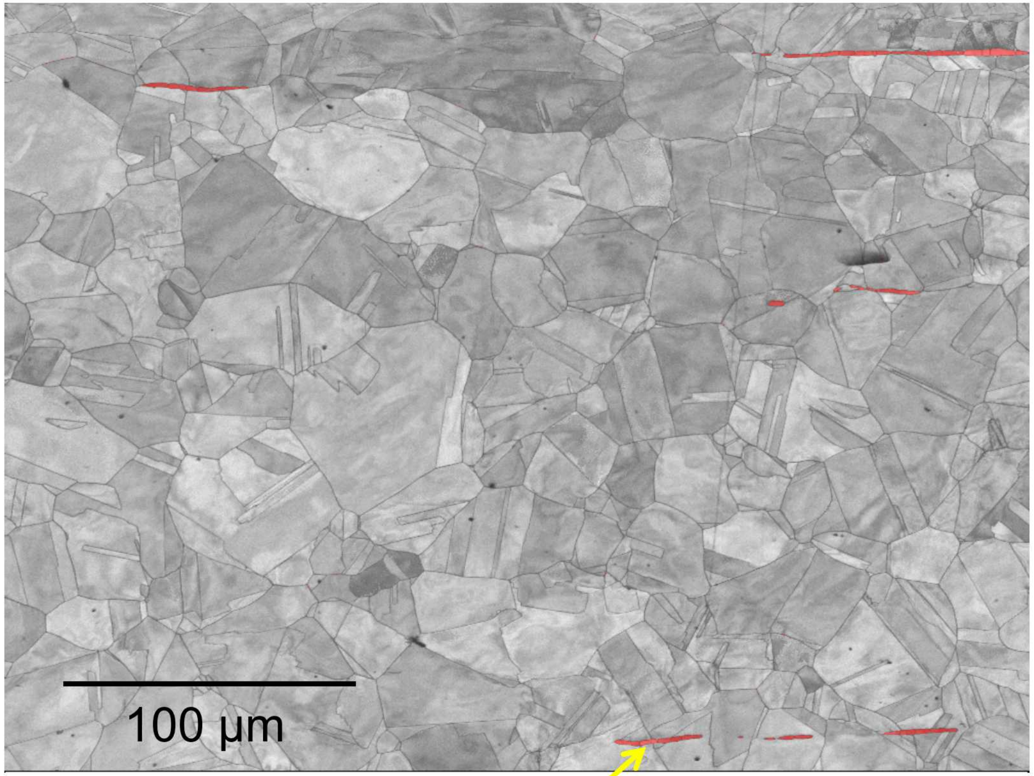


From this, we do not expect Hall-Petch strengthening based on grain size.

Ferrite Stringers in Wrought SS304L

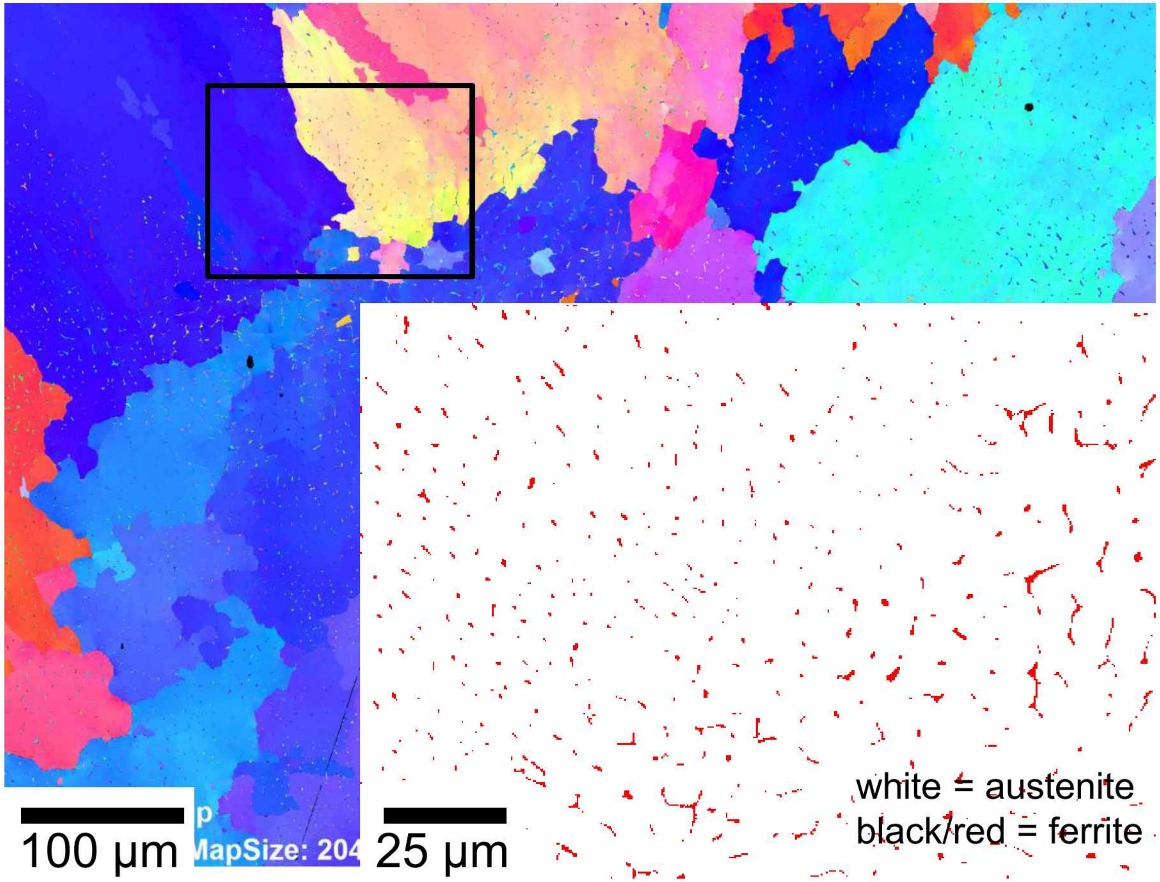


Transverse



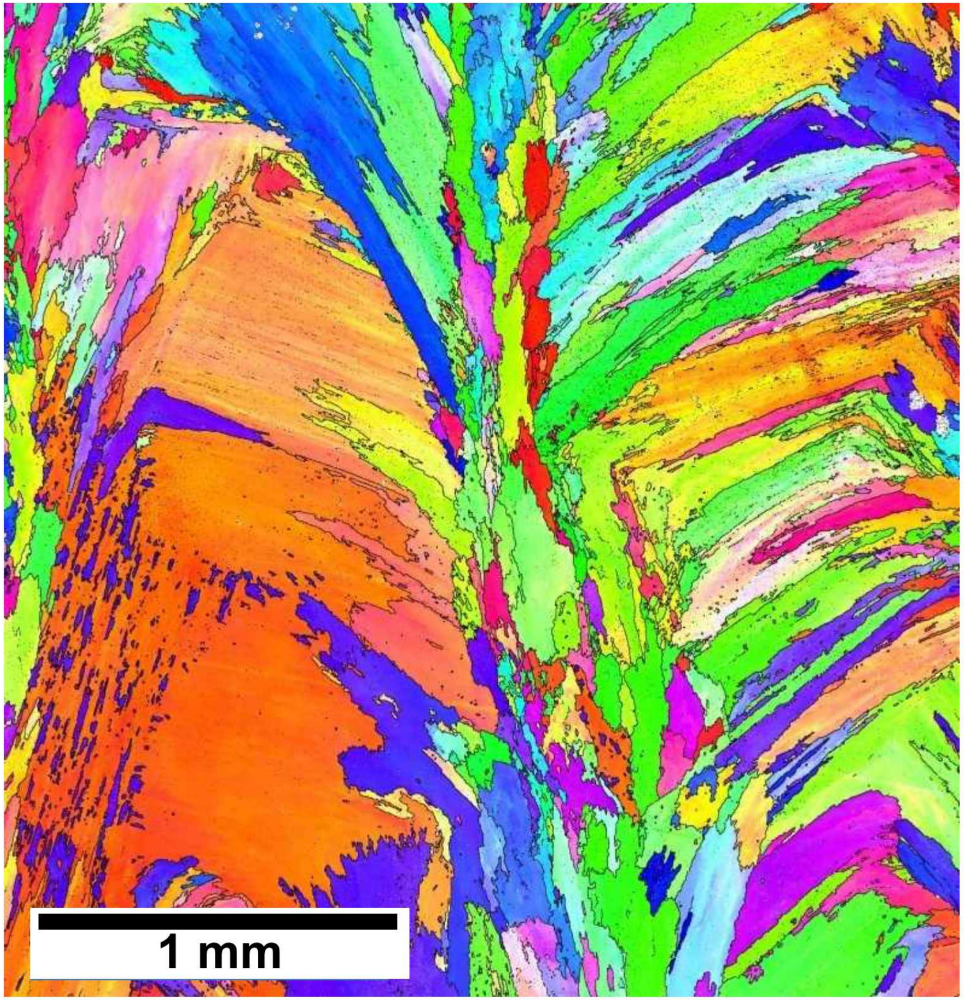
Ferrite stringers

Small ferrite islands could also be responsible for strengthening.

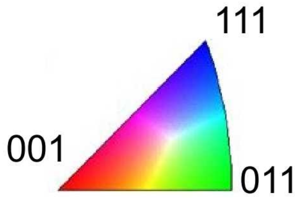


- Small ferrite
  - Average spacing = 5 µm
  - Unlike stringers in wrought
- Initial BCC phase:
  1.2% for Wrought and 2.3% for AM/ 3.8 kW steel (ferritescope)

Grain substructure could contribute to strengthening.

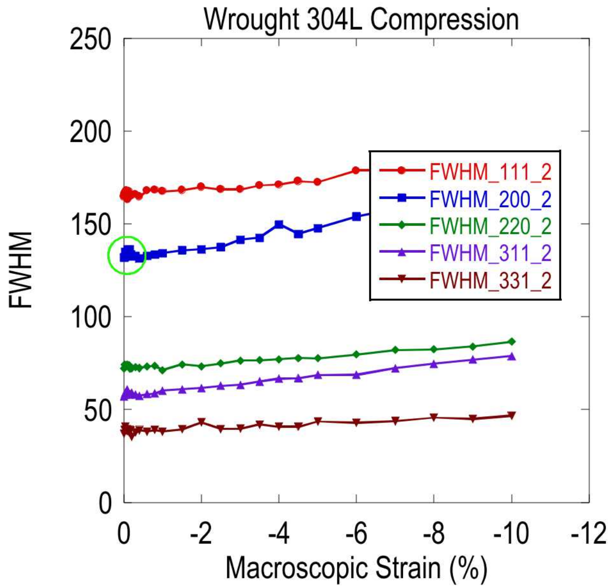


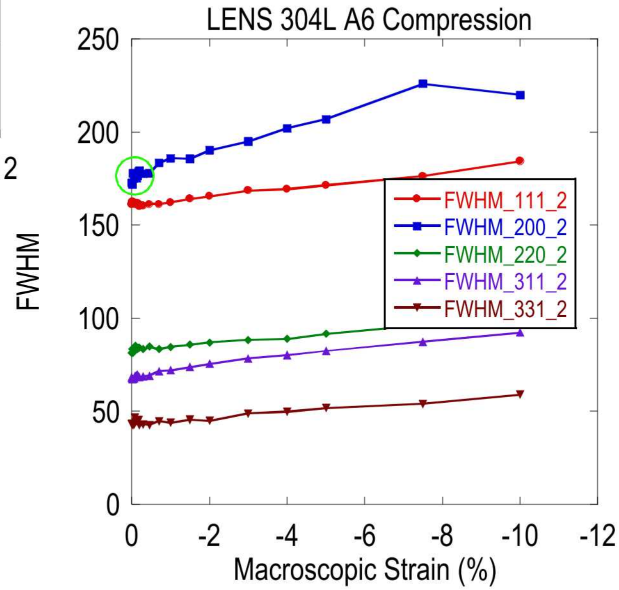
- Subgrains
- Intragrain misorientation implies higher geometrically - necessary density of dislocations.



Neutron Diffraction at LANL is being used to quantify differences in dislocation density and how these change during deformation.

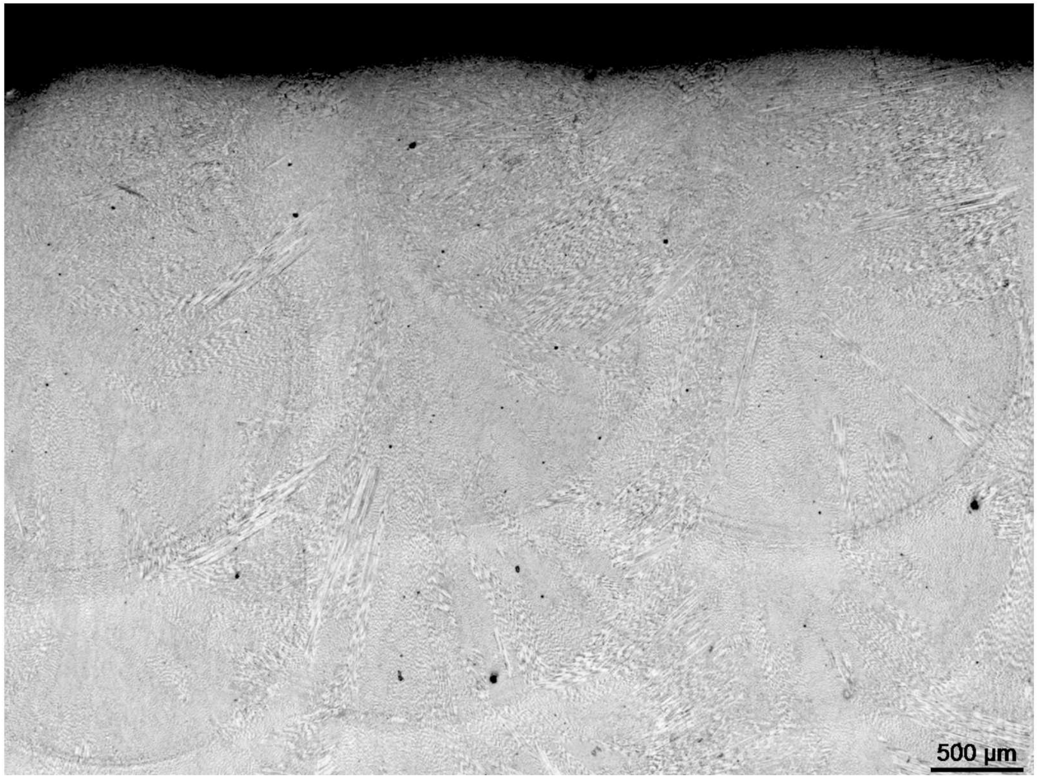
- Diffraction linewidth (FWHM) is increased with greater dislocation density (microstrain) and/or by decreased grain size.
- Initially greater dislocation density in AM material is consistent with observed FWHMs.
- With FWHM increasing during deformation, can expect dislocation density is represented within the diffracted beam width.





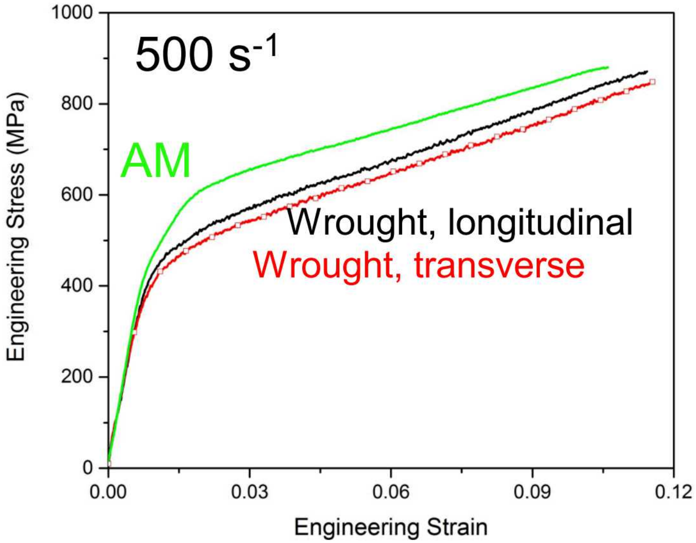
Evidence of oxide dispersions by SEM.

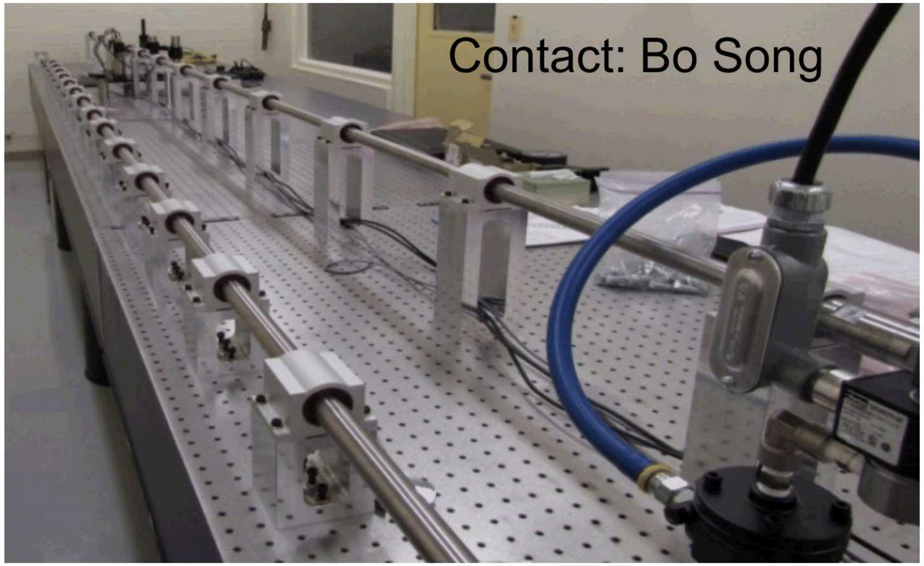
- Oxides are indentified by SEM.
- Initial look shows larger avg. spacing than ferrite in the AM material.
- We speculate that it should have a role but this role is diminished compared with other microstructural effects.

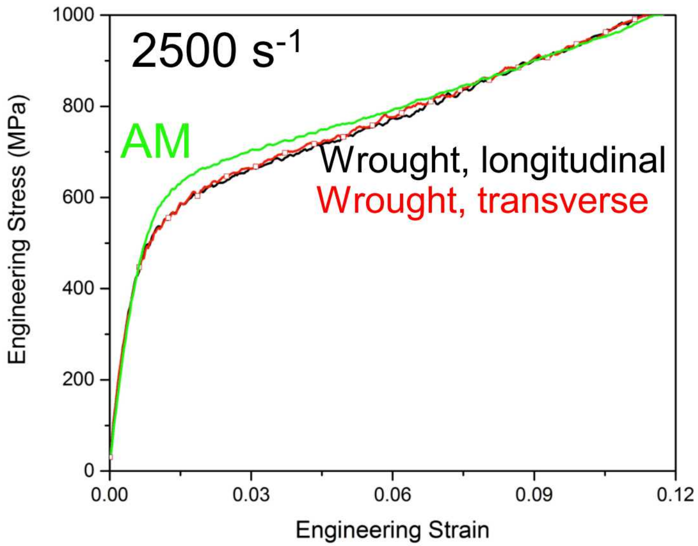


Differences in yield strength vary with strain rate.

- Hopkinson tests (compression and tension) at high strain rate show that LENS high-laser-power SS304L is stronger with wrought.
- Increase in strength is reduced (compared to wrought) when tested at increasingly high strain rates.







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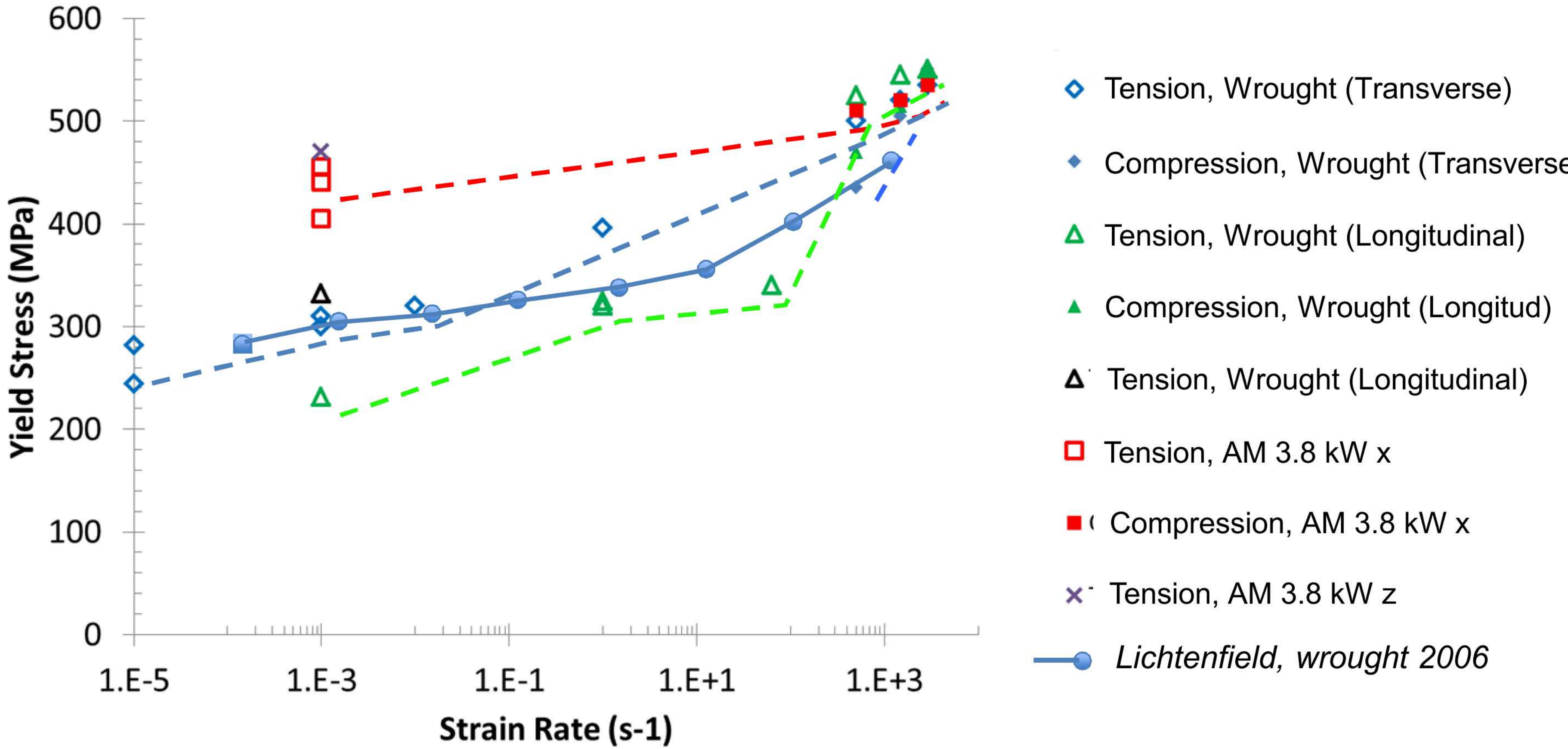
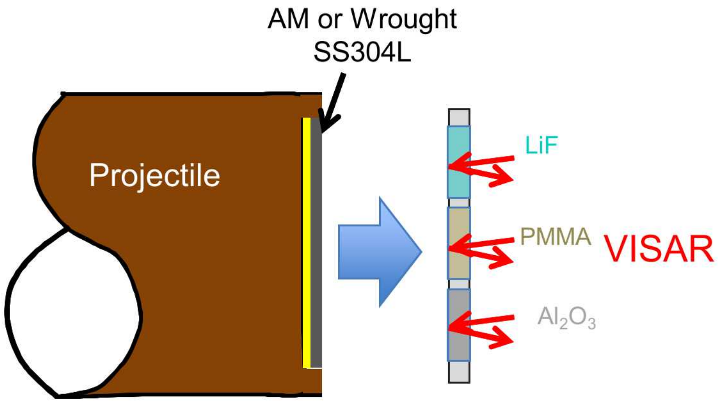


High strain rate impact experiments have been completed.

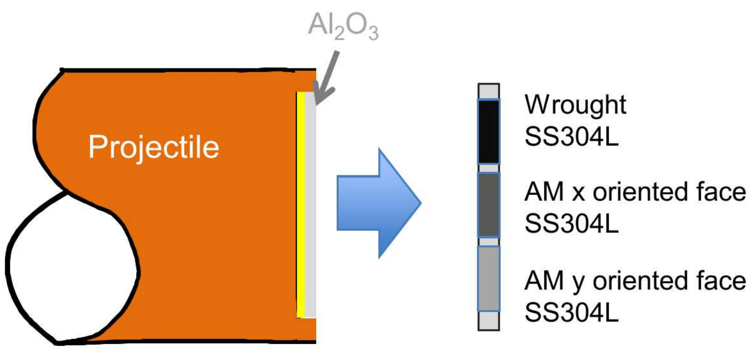
Utilizes Sandia's DICE/Veloce laboratory (J. Wise)

- Reverse Ballistic Impact Tests
  - LENS or wrought SS304L impacting LiF, Al_2O_3, PMMA at v = 80, 200, 350 m/s (up to 60 kbar)
  - uniaxial strain test
  - determines Hugoniot stress-strain relationship

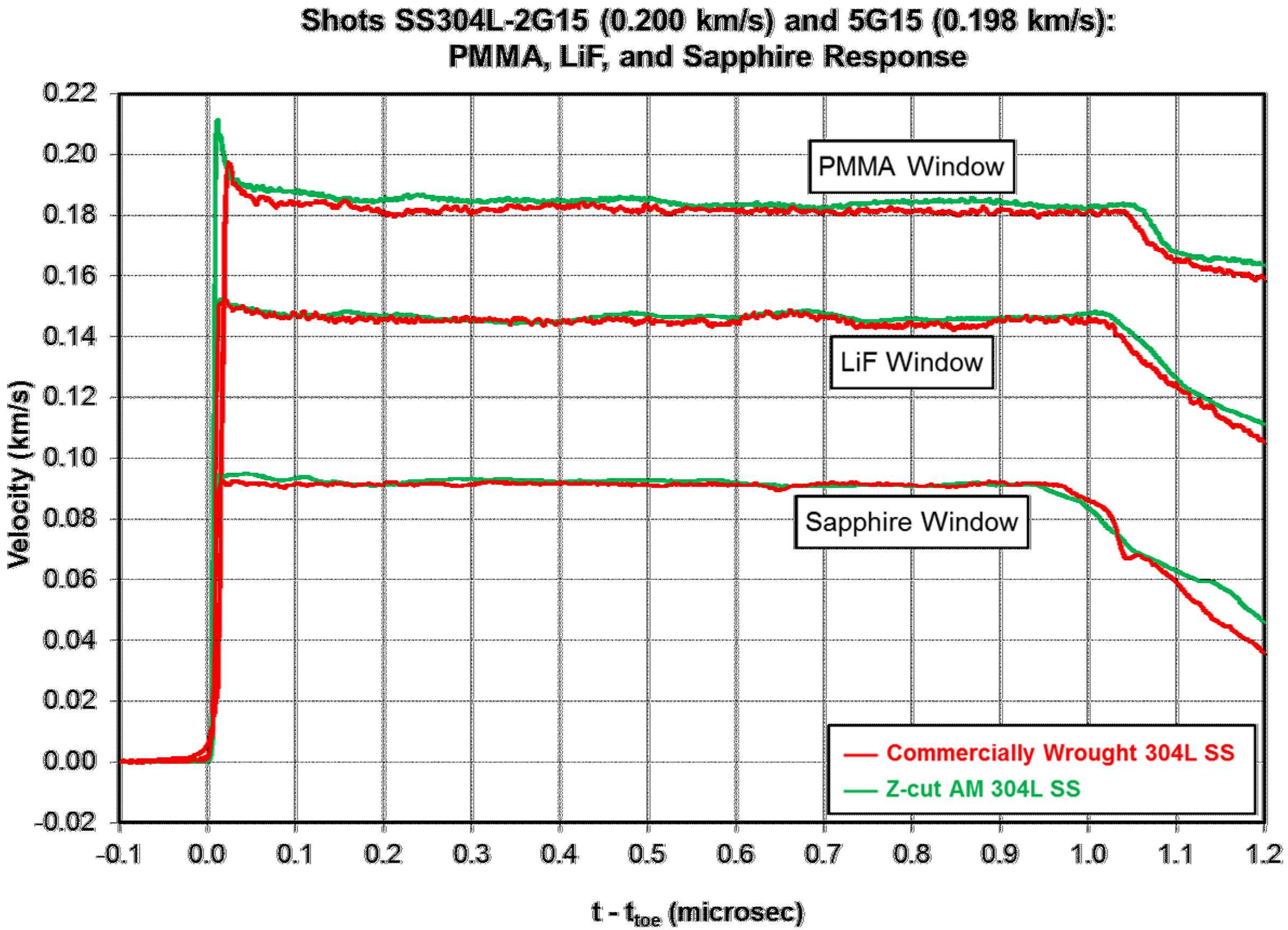


- Forward Ballistic Impact Tests
  - Sapphire impacting LENS (x and y), wrought SS304L
  - Speeds of 80, 200, 350 m/s (up to 60 kbar)
  - Hugoniot elastic limit (HEL) determination

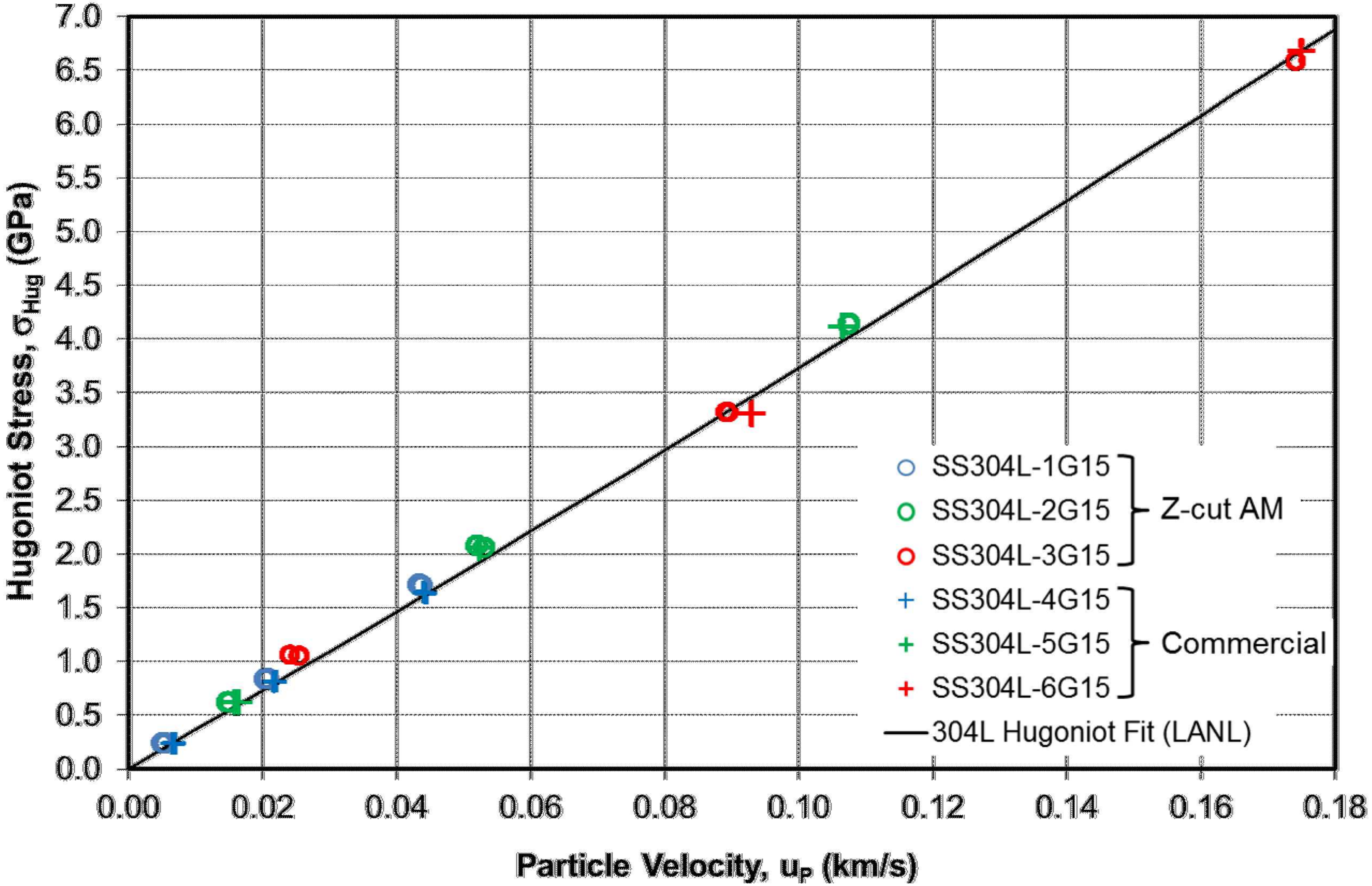
- Forward Ballistic: Spall Strength Tests
  - Sapphire impacting LENS (x and y), wrought SS304L
  - Speeds to be determined



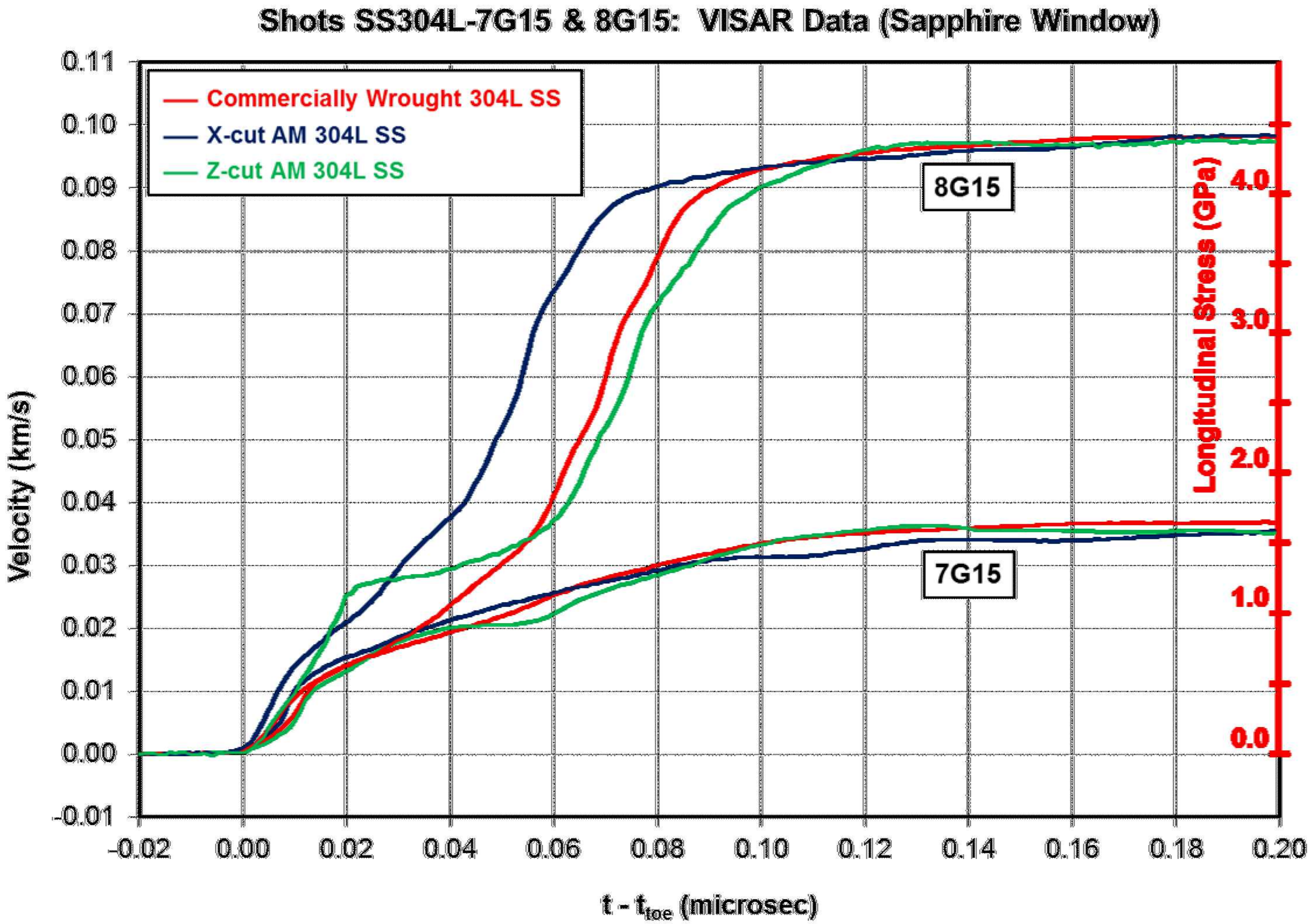
Impact-Surface Motion.



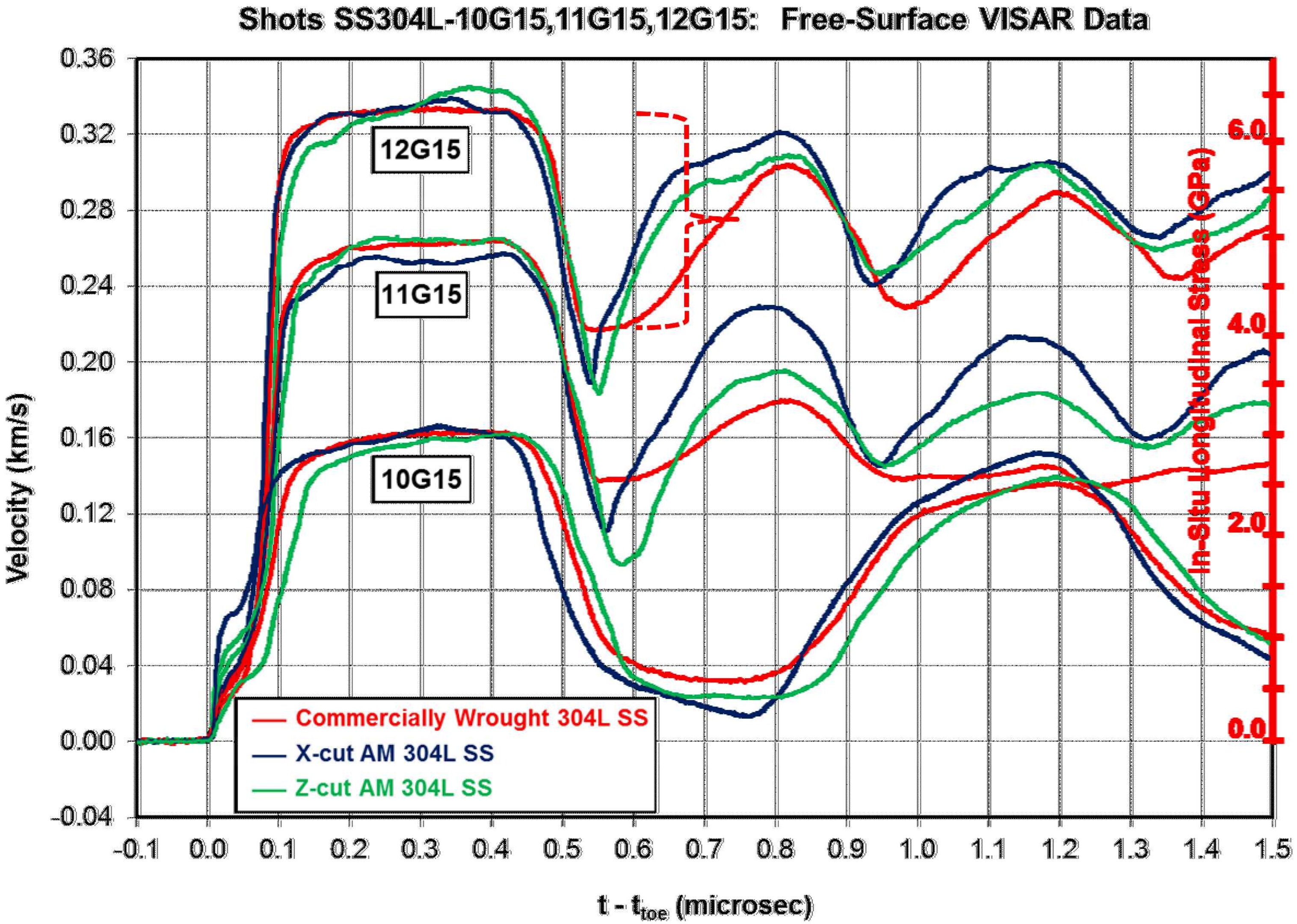
Reverse Ballistic Tests:
Hugoniot Results for AM (3.8 kW) Stainless.



Forward Ballistic Tests : Although variable, the Hugoniot Elastic Limit of AM material exceeds that of wrought.



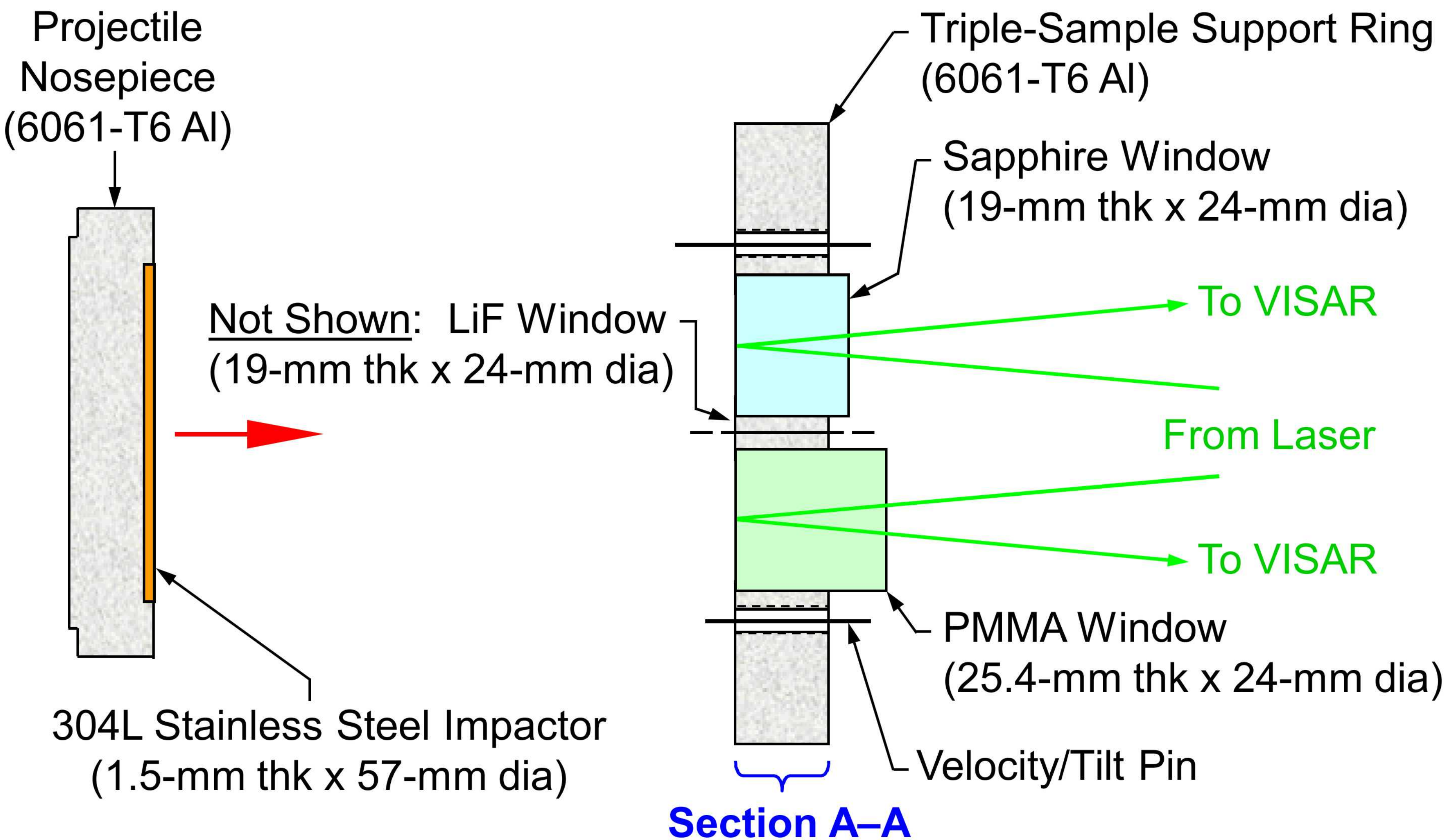
Spall Tests: Spall strengths of AM steel significantly exceed that of wrought.



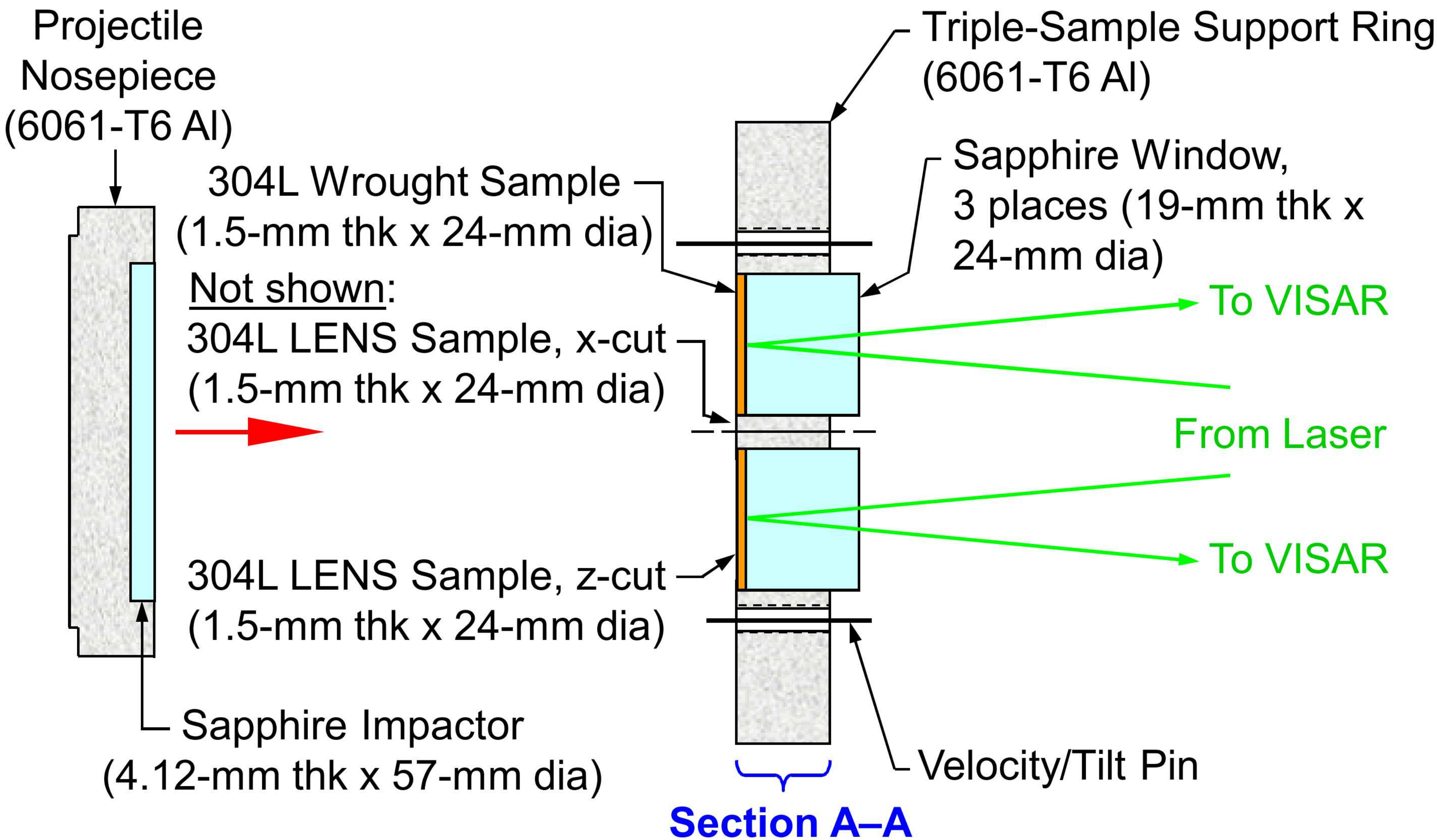
Summary of Mechanical Test Results

- ***Quasi-static testing (3.8 kW, 2.0 kW AM stainless steel 304L):***
  - Increased yield strength in AM compared to wrought.
- ***Dynamic testing (3.8 kW, 2.0 kW AM stainless steel 304L):***
  - Detectable, small differences in yield strength.
- ***Reverse-ballistic testing (3.8 kW AM stainless steel 304L):***
  - Hugoniot EOS data for Z-cut AM samples closely matches current and archival LANL results for conventionally wrought 304L stainless steel.
- ***Forward-ballistic testing (3.8 kW AM stainless steel 304L):***
  - Hugoniot Elastic Limit (HEL) for X-cut and Z-cut AM material exhibits test-to-test/sample-to-sample variability, ranging from ~0.5 to 1.2 GPa, compared to a value of ~0.4 to 0.5 GPa for the conventional material.
  - Spall strength of X-cut (3.27 – 3.36 GPa) and Z-cut (3.71 – 3.91 GPa) AM material significantly exceeds that of conventional material (2.63 – 2.88 GPa).

Reverse ballistic experiments (detailed).



Forward ballistic experiments (detailed).



Spall test configuration (detailed).