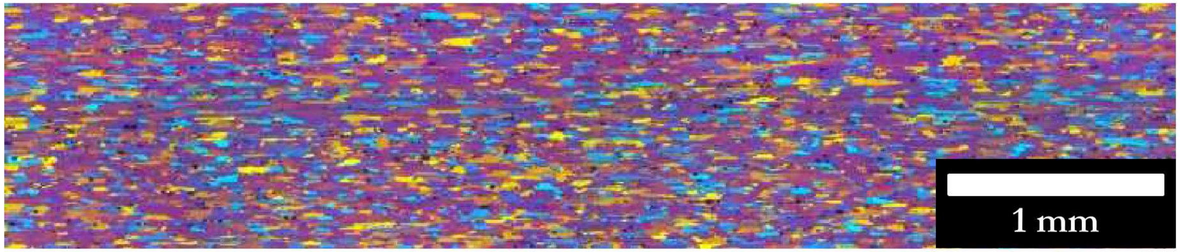
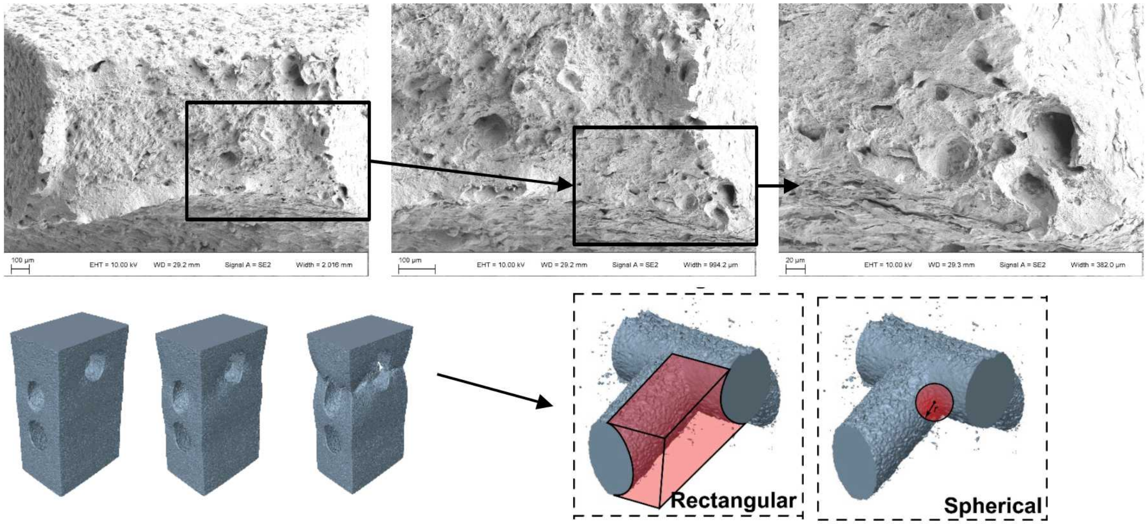
SAND2019-11592PE



Interfaces in Explosively Bonded Stainless Steel



SolAero Interview

September 24, 2019

PRESENTED BY

Thomas A. Ivanoff

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Outline

About Me

- Education
- Postdoctoral work, technical abilities and projects

Explosive Bonding

Other project highlights (ability to adapt to different material systems)

- Carbon fiber reinforced composite
- Glass-to-metal seals
- Robo-Met.3D® serial sectioning system

Interests

Education

<u>The University of Arkansas – 2008 to 2012</u>

B.S. in Physics

B.S. in Mechanical Engineering
- Research: Tribological study of thin films patterned with Ag nano-rods
- Advisor: Min Zou

<u>The University of Texas at Austin – 2012 to 2017</u>

Advisor: Eric Taleff

M.S. in Mechanical Engineering – 2012 to 2014
- *Retrogression-Reaging and Hot Forming of AA7075*

Ph.D. in Mechanical Engineering – 2014 to 2017
- *Reconstruction of Solidification History from Cast Microstructure in Remelted Nickel Alloy 718*
- Additional projects: Hot forming Ti-6Al-4V

Postdoctoral Work

Sandia National Laboratories (Org. 1851) – January 2018 to Present

Mentor: Jonathan Madison
Manager: Cole Yarrington

Primary Research Focus

Develop and advance three-dimensional (3D) characterization techniques and quantitative assessment metrics. Identify potential applications to leverage 3D data for new insights into materials and support of Sandia's mission.

Technical Abilities

Material Mechanics
Mechanical behavior of materials
Materials processing and Solidification
3D characterization and analysis
Failure analysis
Fundamental R&D
Engineering support

Personnel Development

Co-mentor: 1 technologist and 3 undergraduate interns

Productivity/Deliverables

5 Journal Publications
- 4 more in progress

9 Technical Conference Presentations
1 Invited Webinar
3 Technical Posters

Workflow Optimizations

3D characterization codes
Advanced RoboMet.3D capabilities
Data management workflows

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Research Collaborations

The Third Sandia Fracture Challenge
Org. 1528

Micro-CT Processing
Org. 1556

Thermal Spray LDRD
Org. 1344

Defect Detection in AM Metals
Org. 1832, Org. 1444, Org. 5264
Org. 1463

Explosive Bonding
Org. 1831

Fiber Reinforced Composites
Org. 1815, Org. 1513

Engineering Support

Glass-to-metal Seals
Org. 2500

Transformers
Org. 2644

Micro-springs
Org. 2613

Inductors
Org. 2641

Ferro-electrics
Org. 2584

Springs
Org. 2641

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Org. 2641

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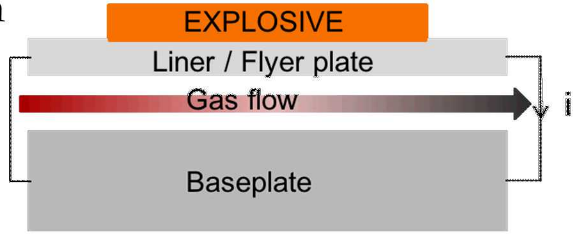
Org. 2584

Springs
Org. 2641

Testing in Extreme Environments with the Z machine

This study explores the use of plastic explosives to close a 6 inch gas flow valve in the Z machine

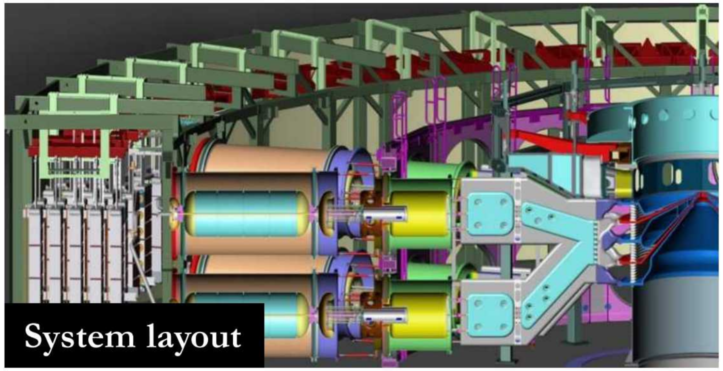
- Precise timing required
- Valve hermetically sealed within ~100 μs
- Cannot contaminate the test environment



Schematic of explosive closure valve

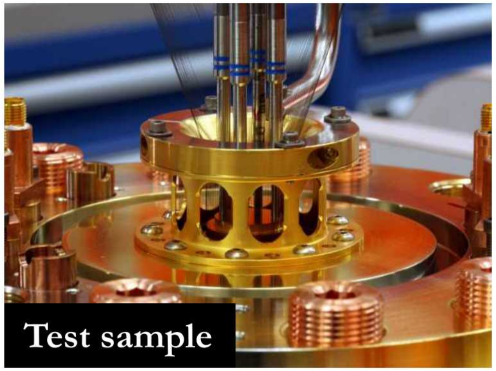
Z machine at Sandia National Laboratories

- World's most powerful and efficient laboratory radiation source
- Pulsed power system creates extreme environments for materials testing



System layout

Test chamber

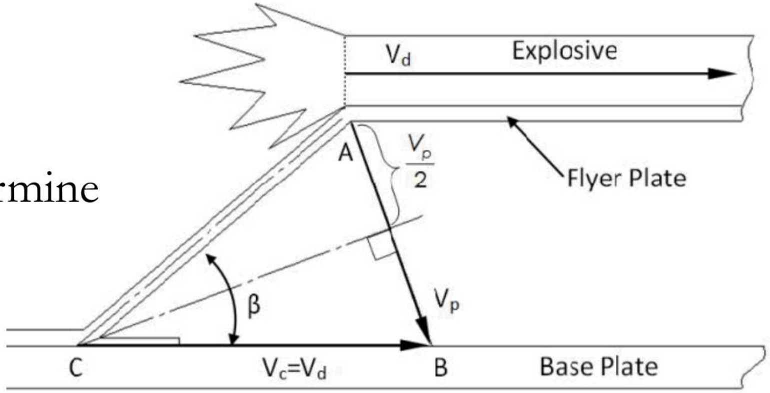


Test sample

Explosive Bonding Parameters

Two primary process parameters determine the quality of a bond

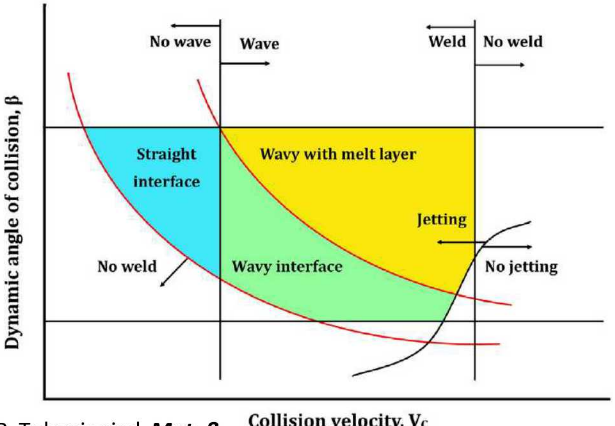
- Collision velocity (V_c)
- Collision angle (β)



J. Ribeiro et al. ***J. Phys, Conf. Series,*** vol. 500 (2014), pp. 052038.1-6

Ammonium nitrate and fuel oil (ANFO)

- Detonation velocities between 2-3 km/s



M. Athar & B. Tolaminejad, ***Mat. & Design,*** vol. 86 (2015), pp. 516-525

Z machine requires plastic explosives

- Detonation velocities between 6-7 km/s

Provides over ANFO:

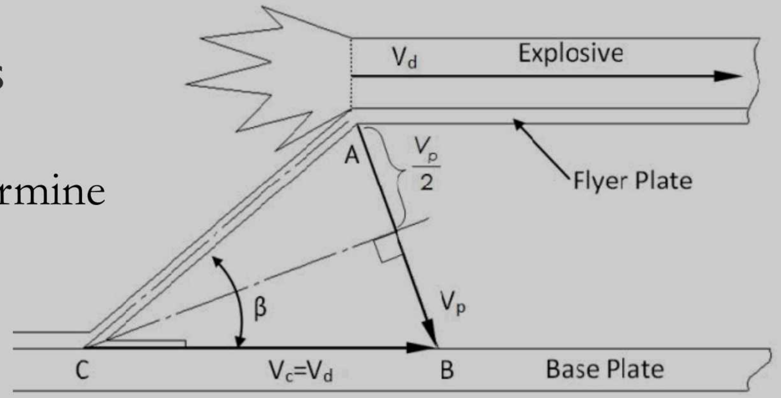
- Cleanliness
- Faster closure speed
- Improved timing

Bonding between two plates. Note incomplete bonding and porosity.

Explosive Bonding Parameters

Two primary process parameters determine the quality of a bond

- Collision velocity (V_c)
- Collision angle (β)



J. Ribeiro et al. ***J. Phys, Conf. Series,*** vol. 500 (2014), pp. 052038.1-6

Ammonium nitrate and fuel oil (ANFO)

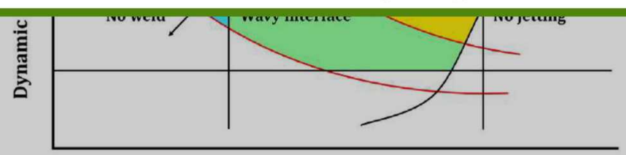
Z machine requires plastic explosives

Characterize bond interfaces in 304L stainless steel plates explosively bonded using plastic explosives using:

Metallography and fractography

Three-dimensional reconstructions from micro-computed tomography

Mechanical testing (lap-shear, microhardness)



M. Athar & B. Tolaminejad, ***Mat. & Design,*** vol. 86 (2015), pp. 516-525

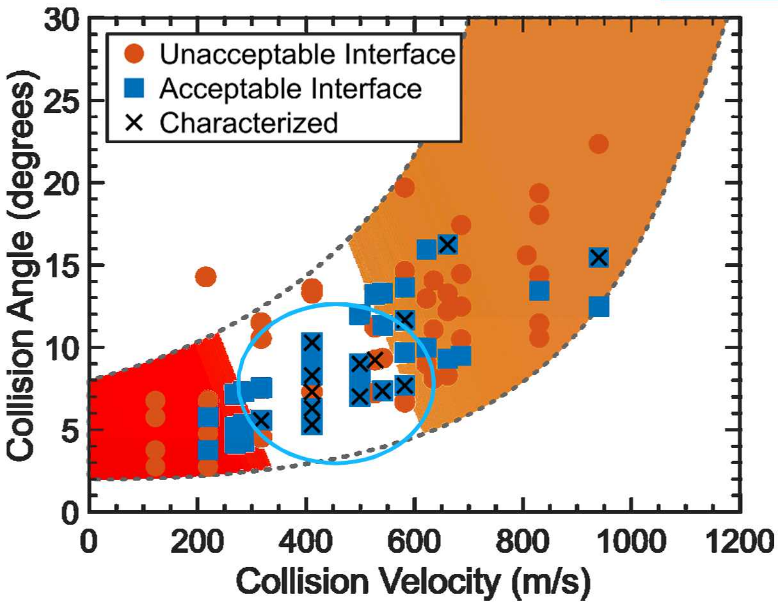
Bonding between two plates. Note incomplete bonding and porosity.

Experimental Setup

Varied Collision angle and velocity

- 15 “acceptable” process settings studied in detail

Each plate sectioned after bonding for micro-computed tomography (µCT) and mechanical testing



Explosive bonding :

Wvenner Saul and Lloyd Payne

Experimental Setup

Varied Collision angle and velocity

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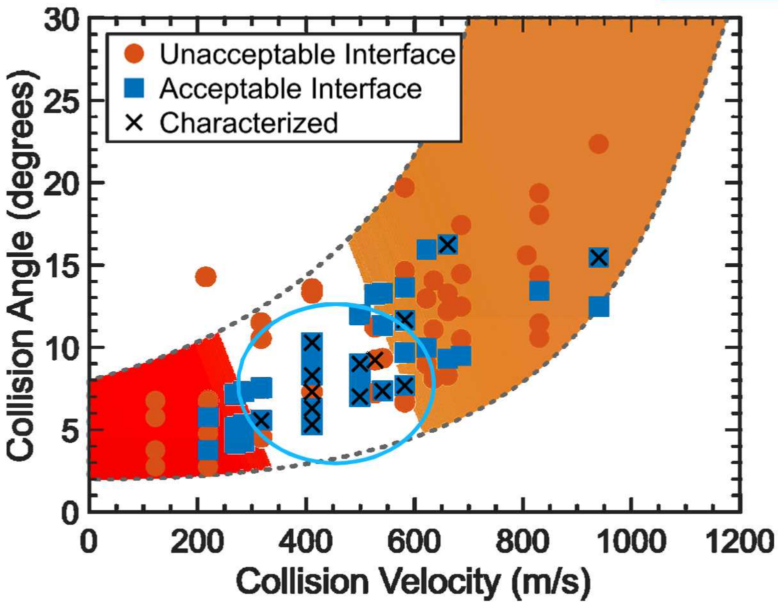
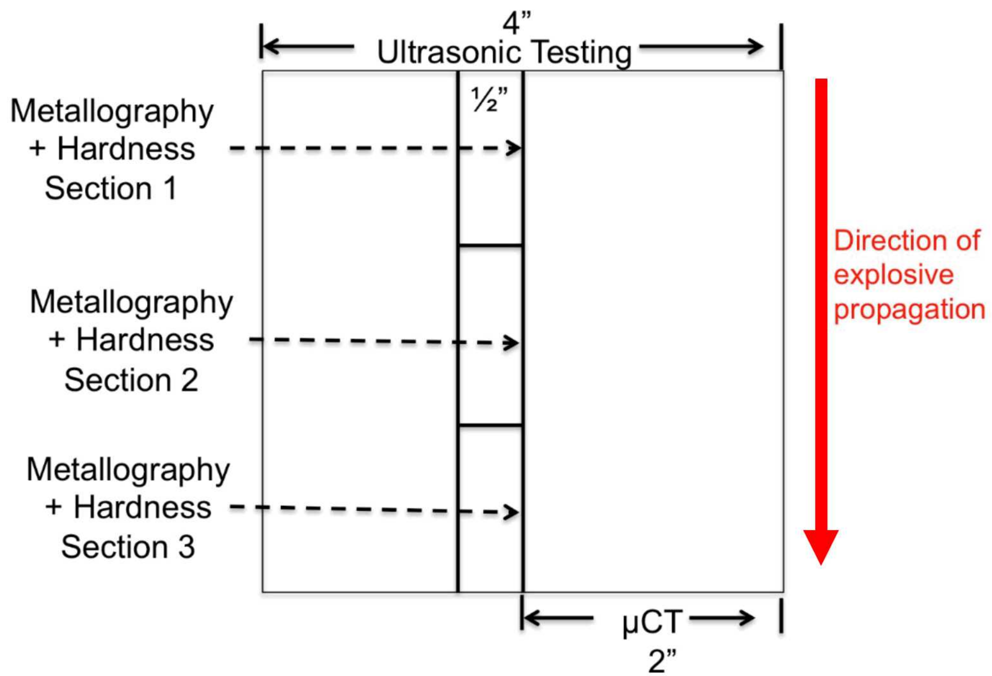




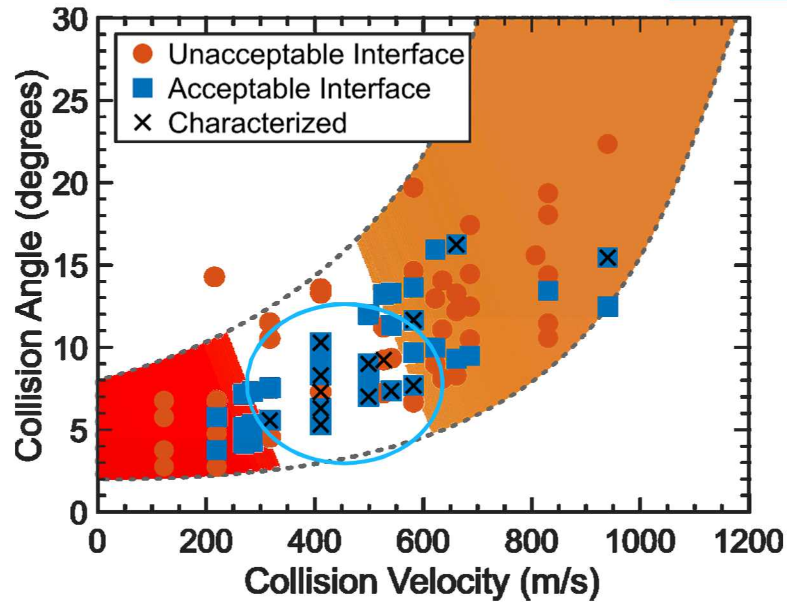
Schematic of the bonded plates demonstrating how material was sectioned for different characterizations.

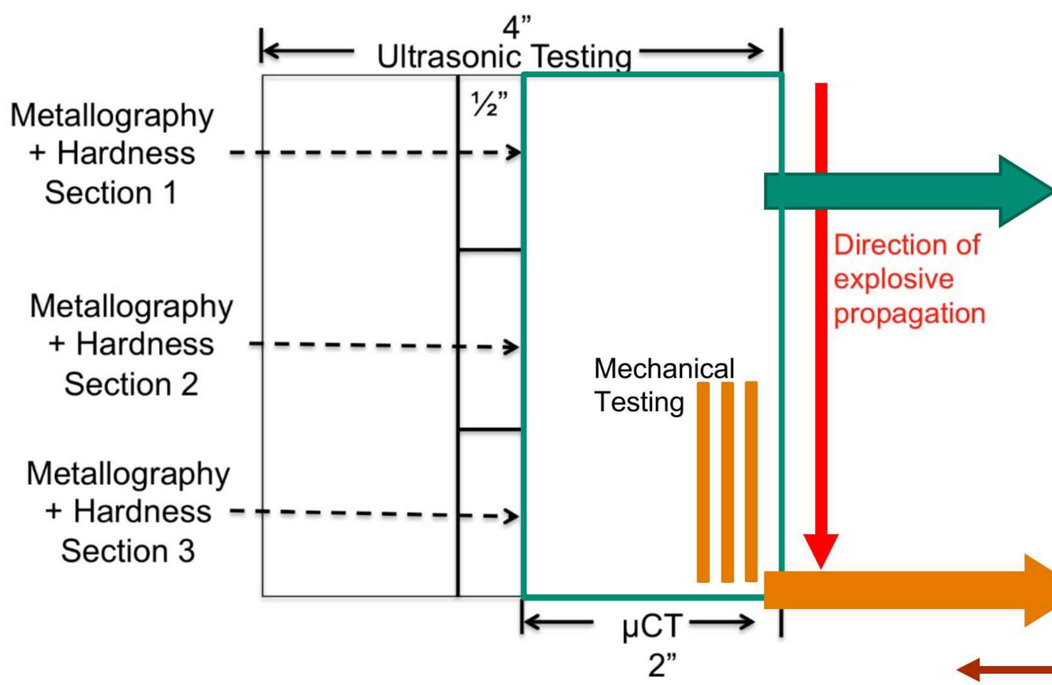
Experimental Setup

Varied Collision angle and velocity

- 15 "acceptable" process settings studied in detail

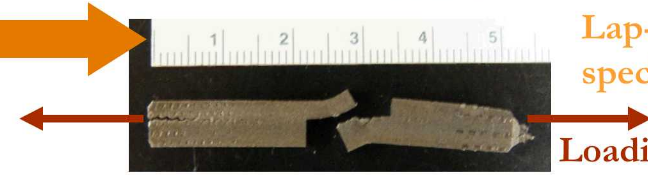
Each plate sectioned after bonding for micro-computed tomography (μCT) and mechanical testing





Schematic of the bonded plates demonstrating how material was sectioned for different characterizations.

Bonded plates characterized using μCT



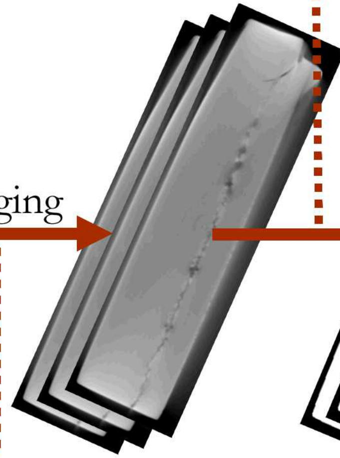
Lap-shear test specimen

Loading direction

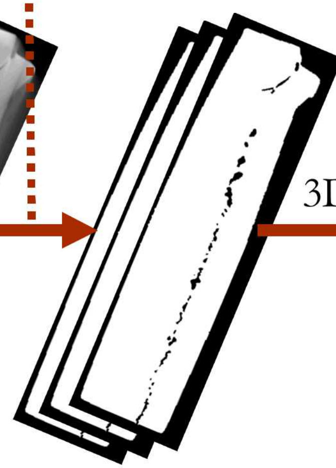
3D Reconstruction Method

Part to be reconstructed

Imaging

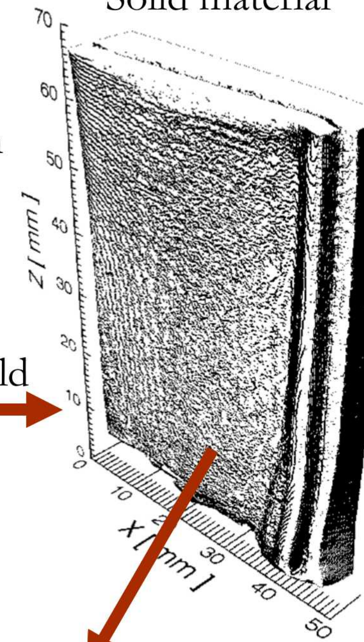


Prepare 2D images for 3D reconstruction

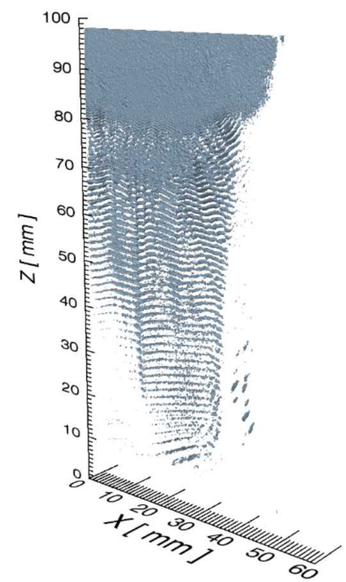


3D Rebuild

Solid material



Unbonded volume



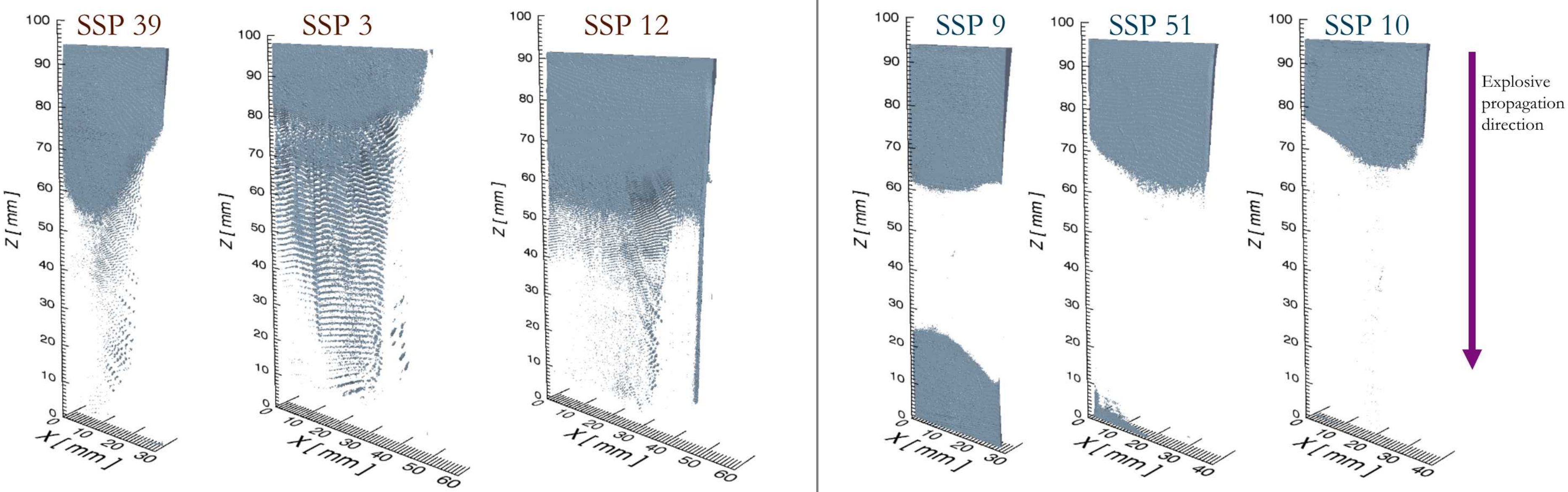
Non-destructive

- Micro-computed tomography

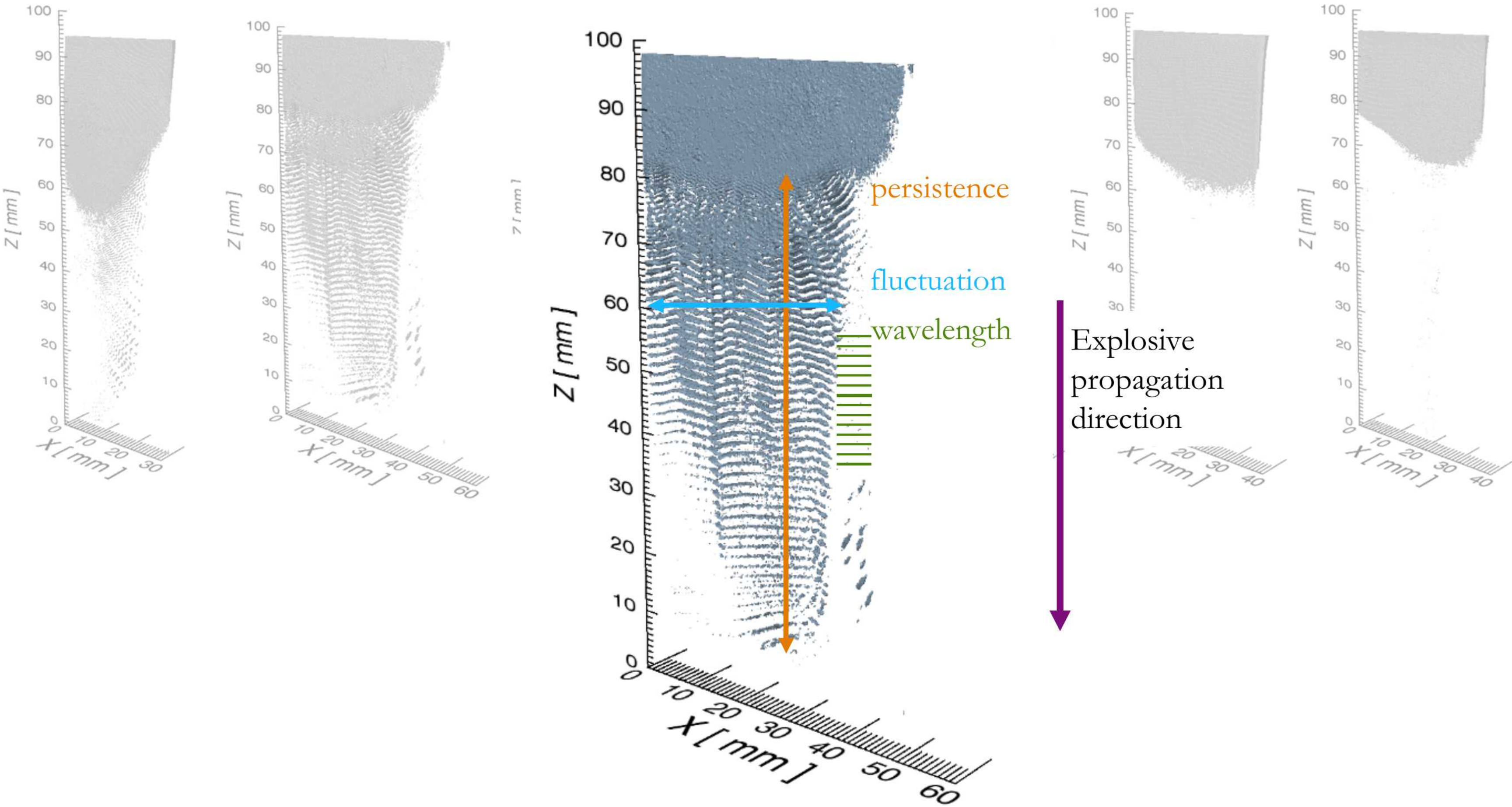
Nikon Avonix M2 225/450 kV Helical Scanner

3D Reconstruction of Unbonded Volumes

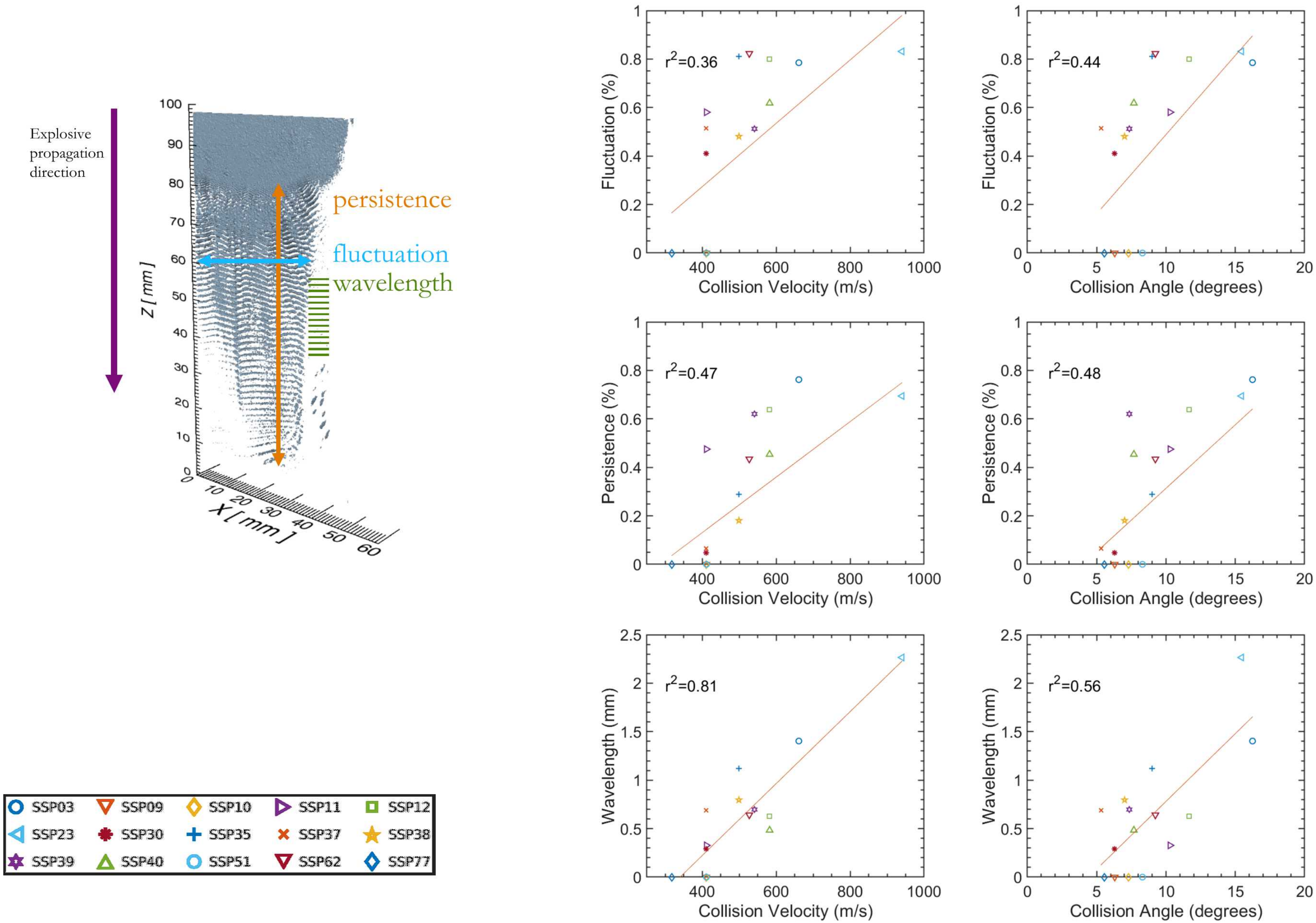
Porous bond interfaces | **Solid bond interfaces**



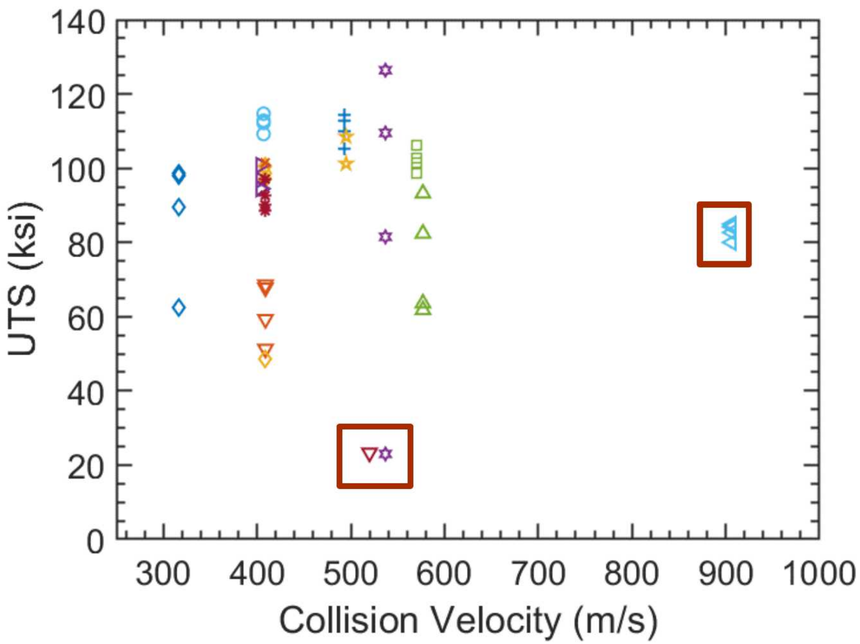
3D Reconstruction of Unbonded Volumes

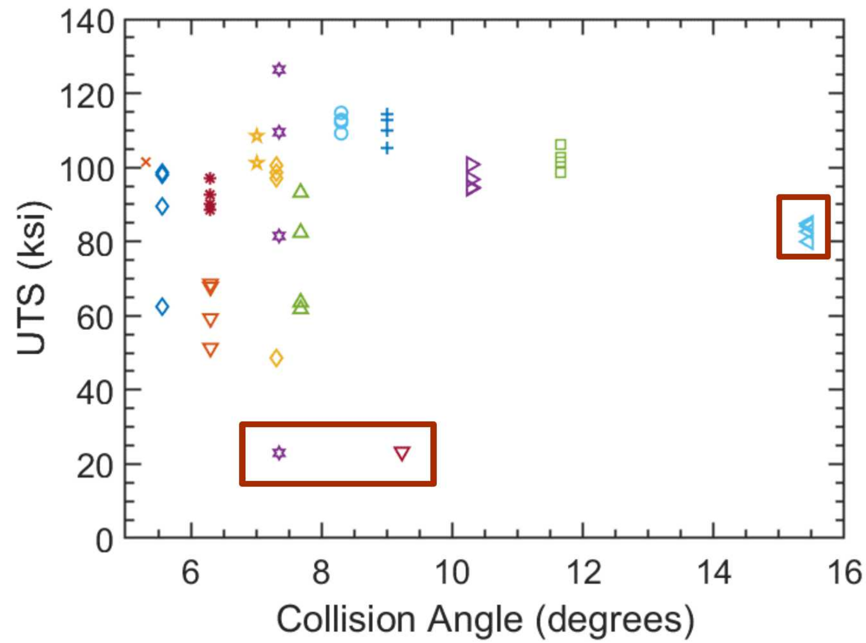


Process Parameter Relationship with Bond Character



UTS from Lap-shear Tensile Tests



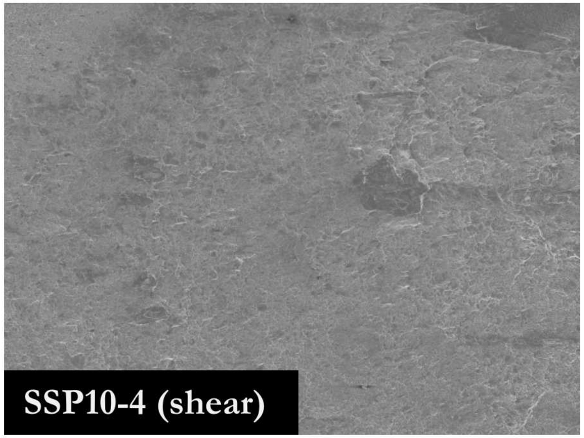


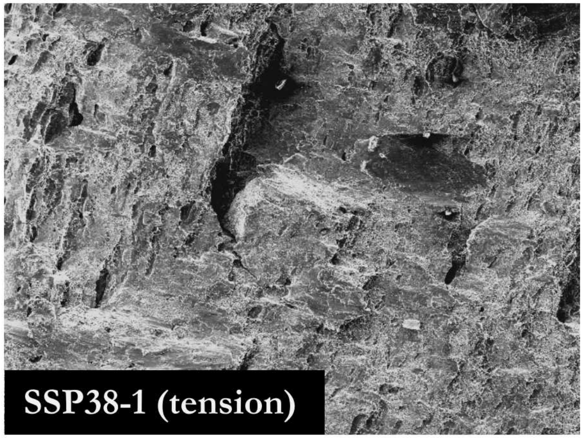
Trends are weak between UTS and collision velocity, collision angle

Outliers mask potential relationships

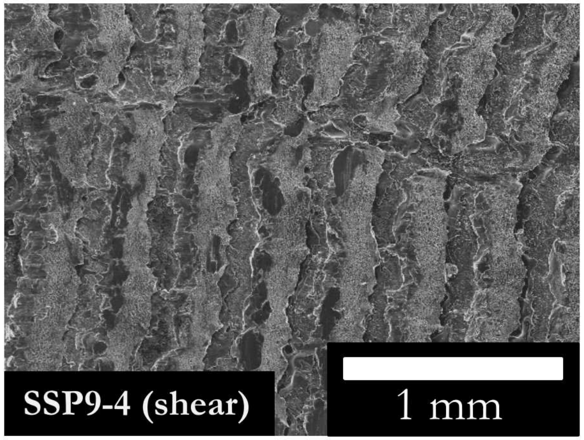
Fractography

Failure in parent material



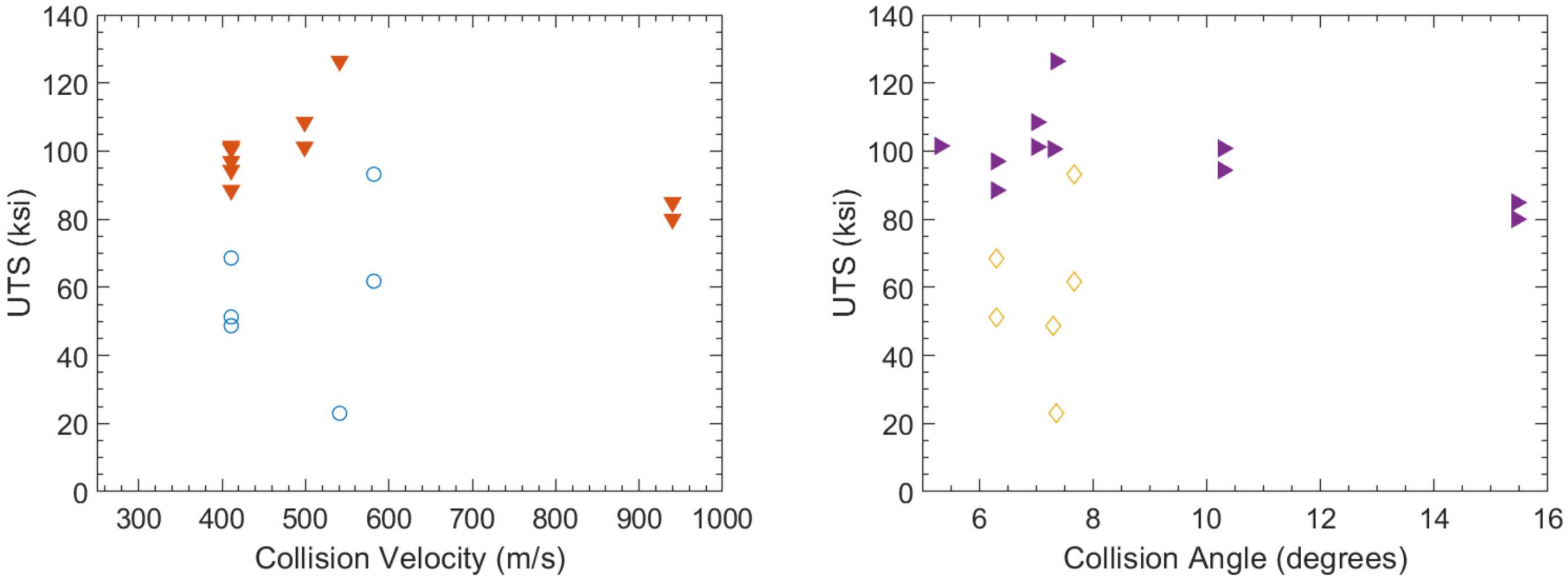


Failure along interface



UTS from Lap-shear Tensile Tests

Filled symbols failed in **Parent Material**
Open symbols failed along **Interface**



1. **Material that failed along interface exhibits no trends**
2. **UTS shows a relationship with collision velocity for parent material failures**

Conclusions

Determined process parameters for bonding using plastic explosives that produce hermetically sealed interfaces in 304L stainless steel plate

- Processing window is narrower than that for ANFO

Overall, bonds demonstrate significant variability in porosity content and strength along the bond length and width

Utilizing multiple characterizations (global or local) can reveal trends and expertise in characterization and analysis can clarify interpretation of complex results

Microstructure of Fiber Reinforced Composite

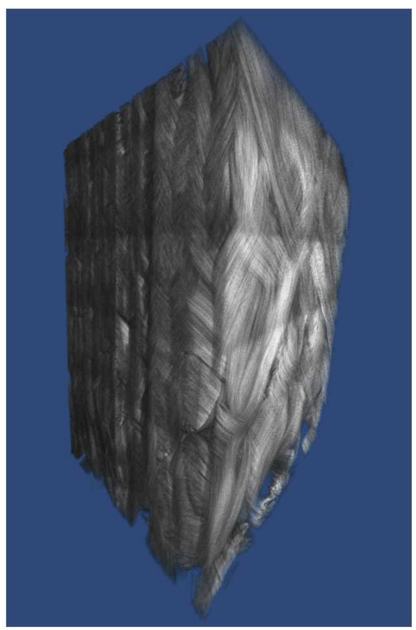
CHALLENGE

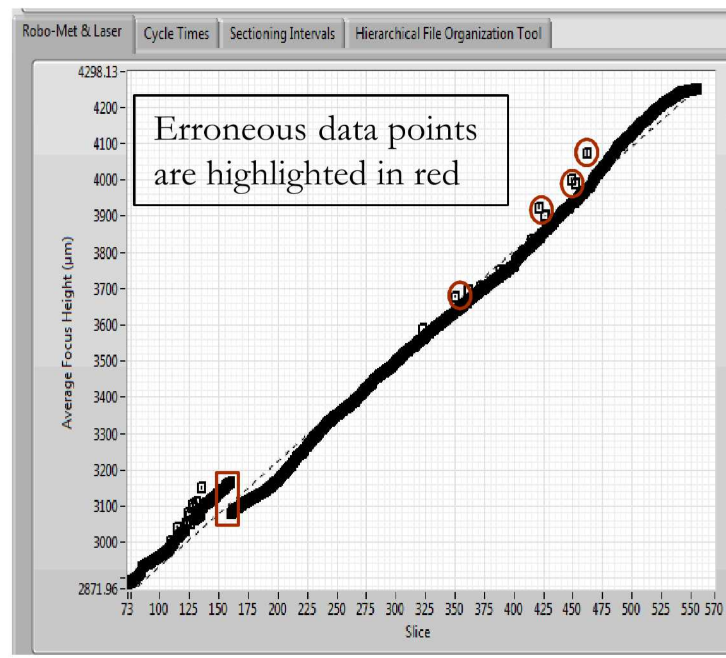
Characterize structure of a woven carbon fiber matrix. Identify **(1) long-range weave pattern** and porosity, **(2) distribution of fibers** within a single weave and **(3) individual fibers**.

FIBER DETAILS

Total volume examined is 10x9x6 mm. Individual fibers are ~5 um in diameter.

Section of the fiber reinforced composite for serial sectioning.





Microstructure of Fiber Reinforced Composite

CHARACTERIZATION

Optical microscopy (5X), 4 x 6 montage, 931 slices (9000x9600 pixels)

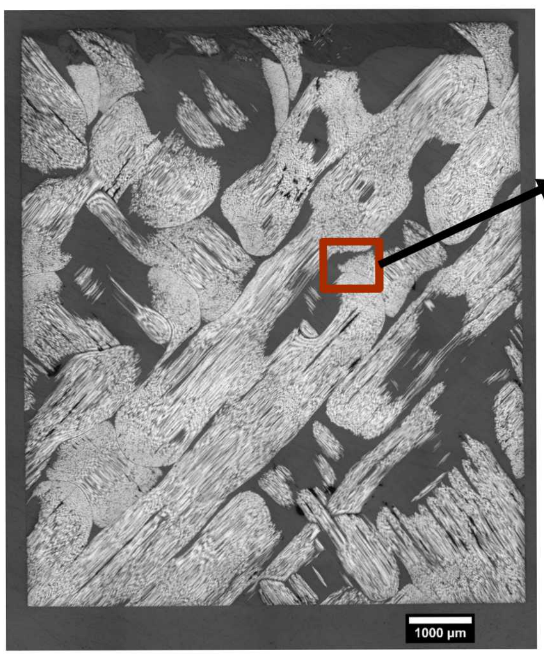
RECONSTRUCTION & ANALYSIS

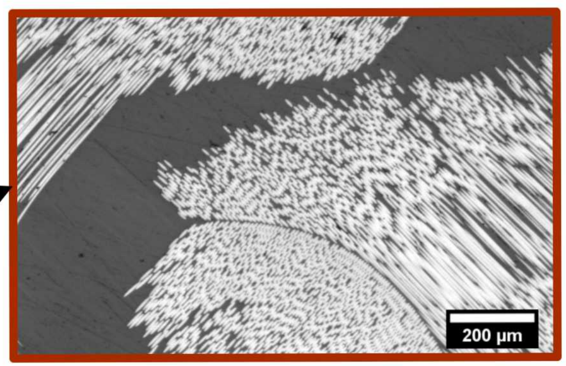
Matlab and FIJI

- *Image Processing*
- *Volumetric Analysis*

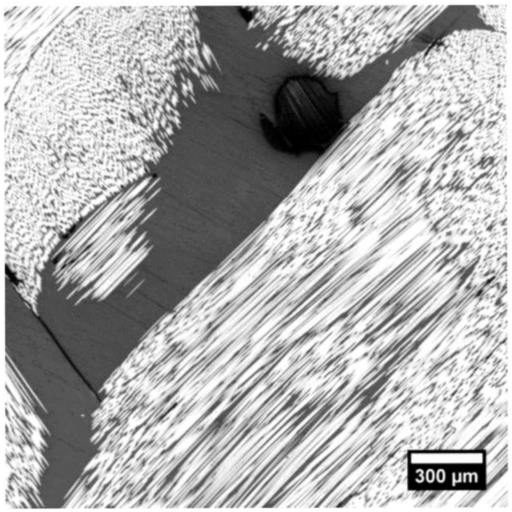
INSIGHTS

- Largest pores exists between the fiber weaves, but porosity still exists within individual weaves.
- Fiber distribution changes when weaves contact/impede each other





Fiber distributions change throughout weaves depending on interaction with other weaves



Cracks in Glass-to-metal Seals

CHALLENGE

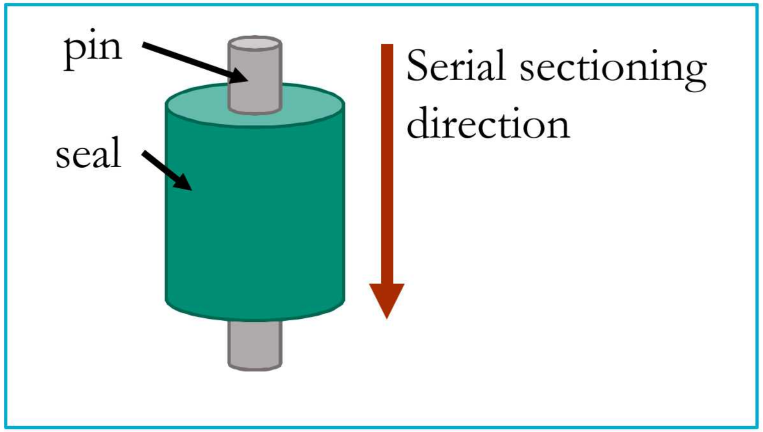
Determine extent of cracking in glass-to-metal seals and optimal method for inspection

DETAILS

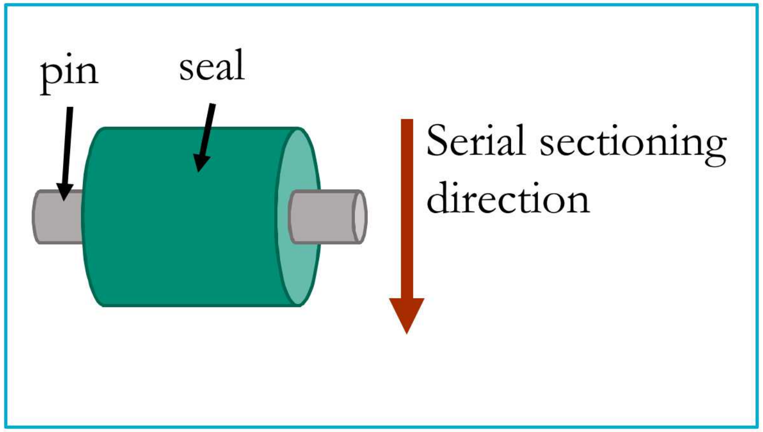
Seals are surrounded by a metal housing; significant residual stress is present in the seal after manufacture

True size/character of cracks cannot be identified without mechanical sectioning; preparing a single plane does not identify crack evolution.

Transverse Mount



Longitudinal Mount

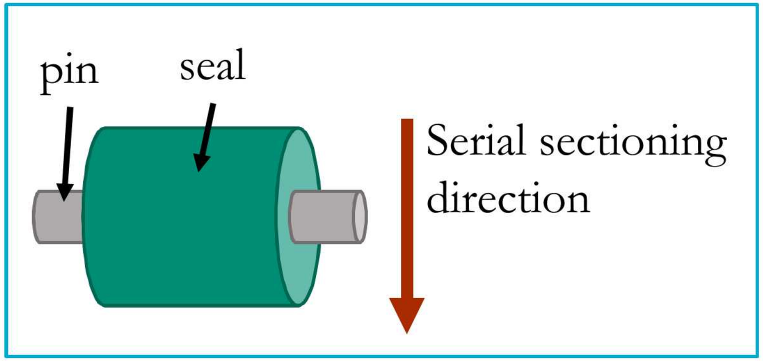


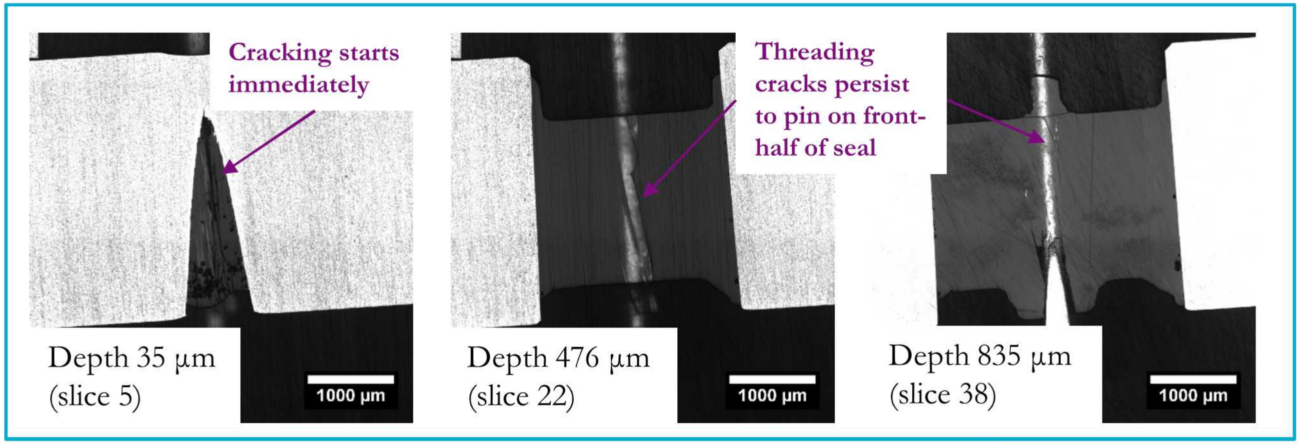
Cracks in Glass-to-metal Seals

Mechanical polishing effects cracks when mounted longitudinally.

Cracks are opened on the front half of the pin but the bottom half of the pin exhibits less cracking.

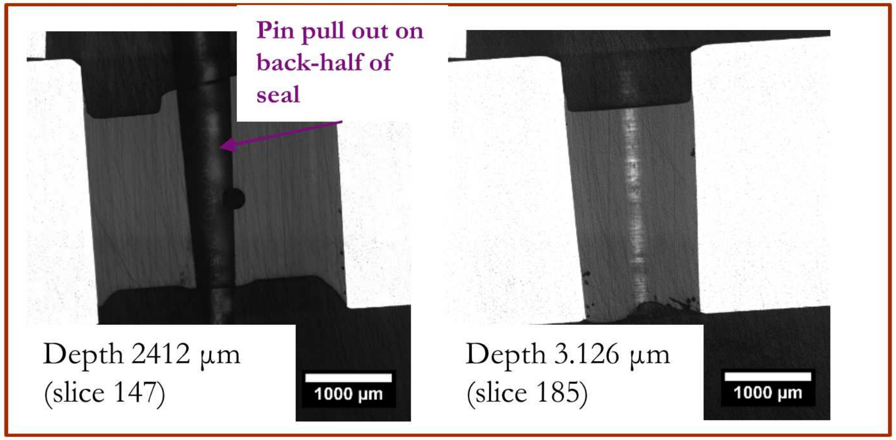
Longitudinal Mount



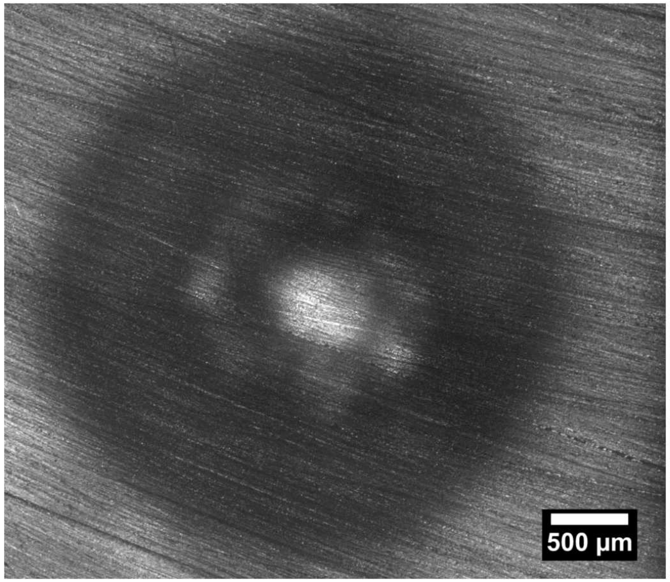


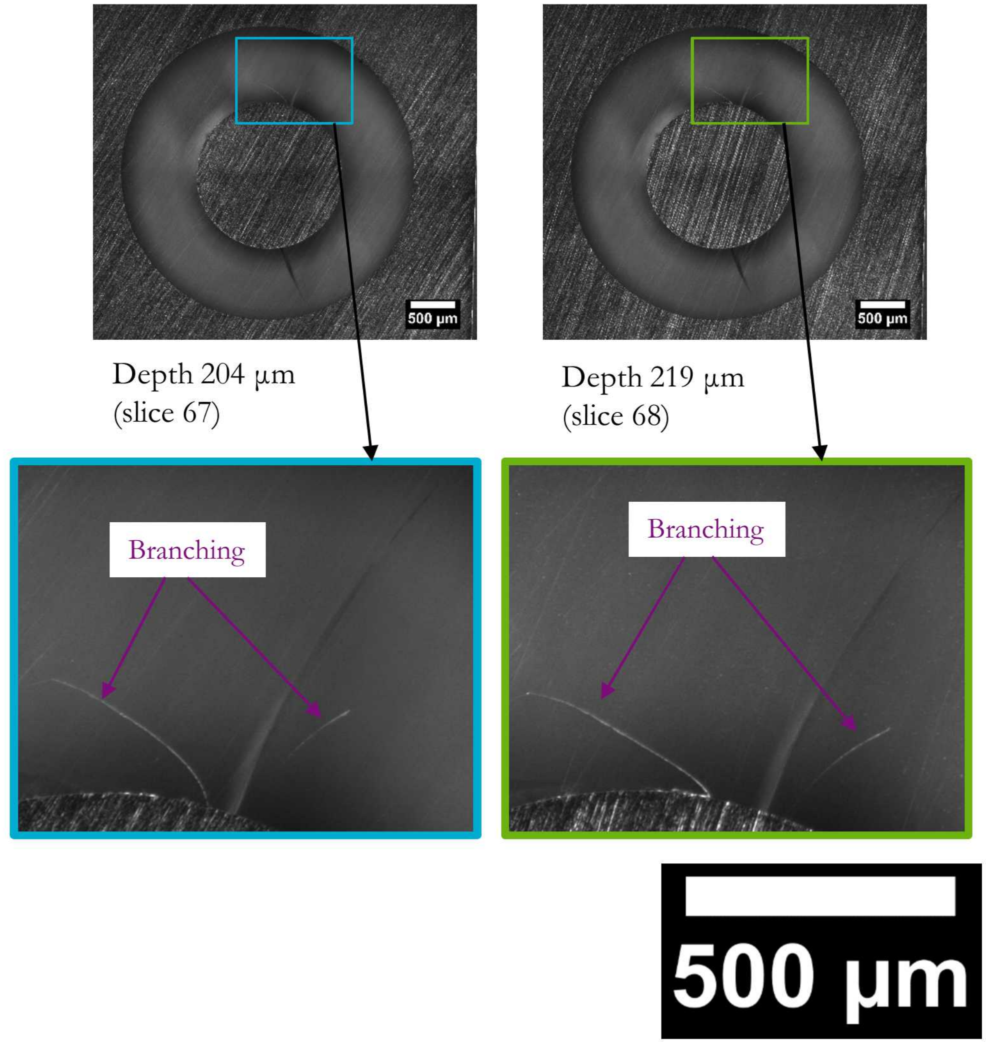
Front half of seal

Back half of seal



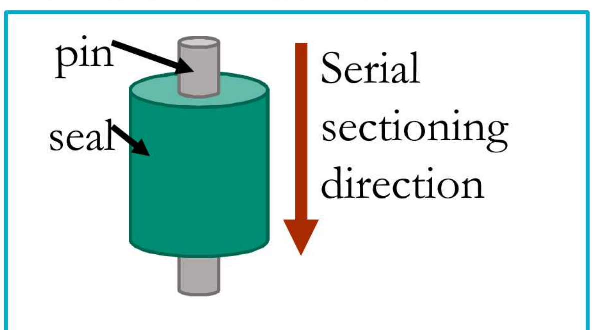
Cracks in Glass-to-metal Seals





Scale bar for enlargements

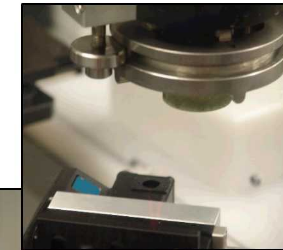
Transverse Mount



Robo-Met.3D

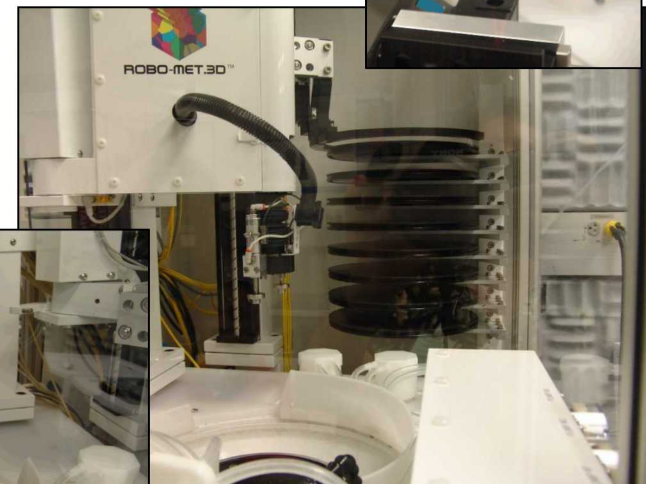
Robo-Met.3D is a fully automated characterization technique for 3D investigations of microstructure using mechanical serial sectioning

- Serial sectioning is the removal of material layer-by-layer and then optical imaging
- Robo-Met.3D provides 3D reconstructions of microstructure across volumes of cubic millimeters at resolutions of microns.



Imaging & Resolution

5X	--	2.10 um/pixel
10X	--	1.05 um/pixel
20X	--	0.53 um/pixel
50X	--	0.21 um/pixel

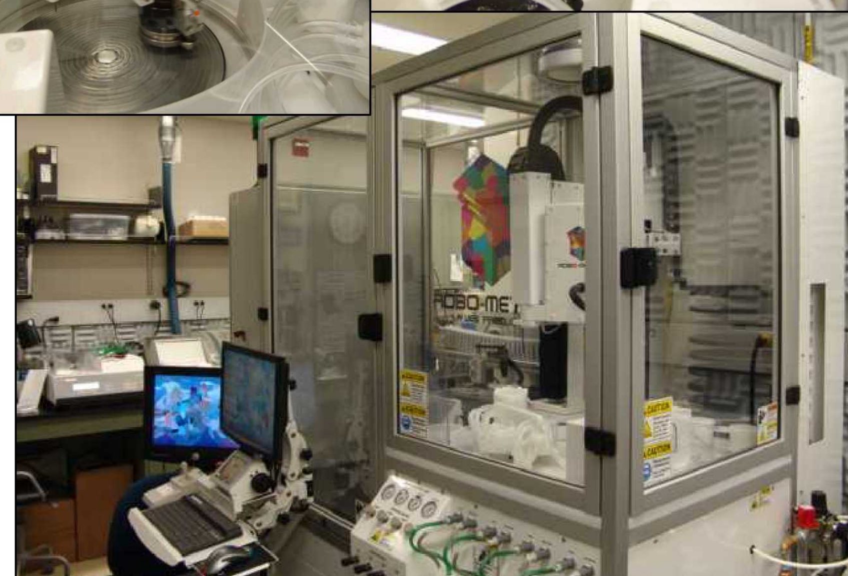


System Components

Automated robotic polisher with variable polishing wheel
Automated high resolution inverted microscope with montage imaging
Dual internal ultrasonic cleaning stations
Three internal compact chemical etching stages
External operator station for real-time observation of data collection

Benefits

Sectioning rates up to 10 times the baseline manual process
Elimination of variability caused by human handling or error due to automated handling of specimens
Precise repeatability and command over imaging location, illumination, contrast, exposure and feature focus
Demonstrated repeatable sectioning thicknesses from 0.2 – 10 mm per slice
Documented slice rates of up to 20 slices per hour
Applicable to high and low strength metals (e.g. Al, Cu, Ti, Steel, Ni), thermal spray & geology samples



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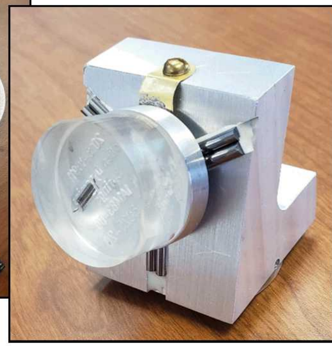
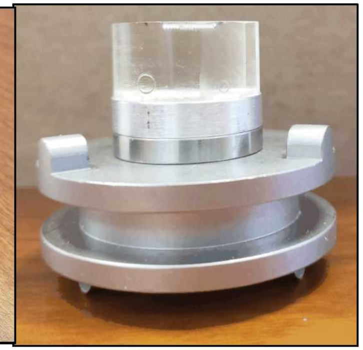
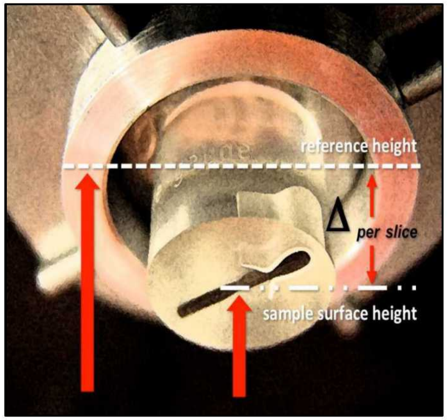
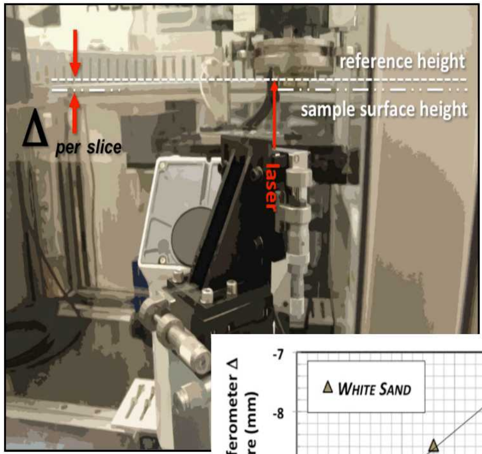
Robo-Met.3D System Advances

Kinematic specimen holder





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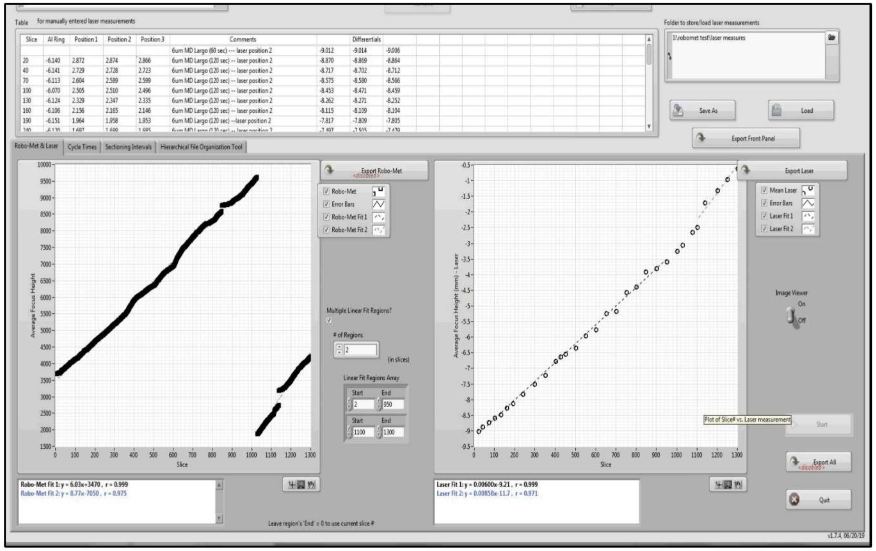
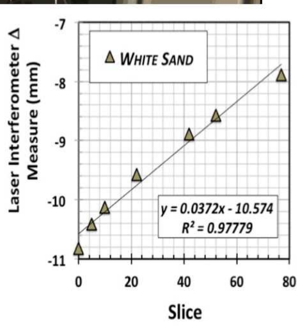
D.O.E. Commercial Software Copyright - J.D. Madison, G.A.Poulter, E.M. Huffman, DoE Commercial Software Copyright, SCR 2075.0 - 'Mechanical Serial-Sectioning Data Assistant (MECH-SSDA) v1.3'





SANDIA TECHNICAL ADVANCE SD#**13742**

U.S. Patent No. 10,260,865 - J.D. Madison, E.M. Huffman, "HIGH RESOLUTION, NON-CONTACT REMOVAL RATE MODULE FOR SERIAL SECTIONING", issued April 16, 2019, SD13742.1/S142462

Questions

Publications

T. A. Ivanoff, T. J. Watt, and E. M. Taleff. "Characterization of Solidification Microstructures in Vacuum Arc Remelted Nickel Alloy 718," *Metallurgical and Materials Transactions B*, vol. 50, no. 2, 2019, pp. 700-715.

T. A. Ivanoff, J. T. Carter, L. G. Hector, and E. M. Taleff. "Retrogression and Reaging Applied to Warm Forming of High-strength Aluminum Alloy AA7075-T6 Sheet," *Metallurgical and Materials Transactions A*, vol. 50, no. 3, 2019, pp. 1545-1561.

J. A. Mitchell, **T. A. Ivanoff**, D. Dagel, J. D. Madison, and B. H. Jared "Linking Pyrometry to Porosity in Additively Manufactured Metals," *Additive Manufacturing*, 2019, pp. 1-2.

- Accepted with revisions

S. L. B. Kramer, **T. A. Ivanoff**, J. D. Madison, and A. P. Lentfer. "Evolution of Damage in an Additively Manufactured 316L SS Structure: experimental reinvestigation of the third Sandia Fracture Challenge," *International Journal of Fracture*, vol. 218, no. 1-2, 2019, pp. 63-84.

S. L. B. Kramer, …, **T. A. Ivanoff**, …, et. al. "The Third Sandia Fracture Challenge: predictions of ductile fracture in additively manufactured metal," *International Journal of Fracture*, vol. 218, no. 1-2, 2019, pp. 5-61.

N. M. Heckman, **T. A. Ivanoff**, A. M. Roach, B. H. Jared, J. Rodelas, D. J. Tung, H. J. Brown-Shacklee, T. Huber, D. J. Saiz, J. R. Koepke, J. D. Madison, B. C. Salzbrenner, L. P. Swiler, R. Jones, B. L. Boyce. "Robust processing parameters for additively manufactured 316L stainless steel revealed through high-throughput tensile testing."

- Submitting

T. A. Ivanoff, O. Underwood, J. D. Madison, L. Deibler, J. Rodelas, C. Finfrock, "Influence of Processing Parameters on Interface Character and Bond Quality in Explosively Bonded 304L Stainless Steel."

- In progress

T. A. Ivanoff, J. A. Mitchell, J. D. Madison, D. Dagel, D. Saiz, J. R. Koepke and B. Jared. "Correlation of In-situ Thermal Pyrometry Signatures with Porosity Defects in Additively Manufactured 316L Stainless Steel."

- In progress

T. A. Ivanoff and J. D. Madison. "Influence of Segmentation on the Quantitative Analysis of Three-dimensional Characterizations,"

- In progress

Technical Presentations

T. A. Ivanoff, J. D. Madison, N. W. Moore, and A. Olson. "Three-Dimensional Characterization of Microstructure and Elemental Segregation of Thermal Spray Coatings," TMS 149th Annual Meeting & Exhibition (TMS 2020), San Diego, CA, February 2020.

- **Abstract Accepted**

T. A. Ivanoff, J. A. Mitchell, J. D. Madison, D. Dagel, D. Saiz, J. R. Koepke and B. Jared. "Correlation of Porosity Defects with In-situ Pyrometry in AM316L Stainless Steel," MS&T 2019, Portland, OR, September – October 2019.

- **Monday September 27th**

T. A. Ivanoff, S. L. B. Kramer, J. D. Madison and A. P. Leftner. "3D Characterizations of Internal Porosity and Surface Topology and Their Influence on Local Fracture Behavior in AM 316L Stainless Steel," Solid FreeForm Fabrication 2019, Austin, TX, August 2019.

T. A. Ivanoff, O. D. Underwood, J. D. Madison. "Three-dimensional Materials Science and Mechanical Serial Sectioning for Characterization of Microstructure," ASM Webinar sponsored by UES, July 2019.

T. A. Ivanoff, O. D. Underwood, J. Madison, L. A. Deibler, and J. Rodelas, "Characterization of Interfacial Bond Surfaces in Explosively Bonded 304L Stainless Steel," *2019 TMS Annual Meeting & Exhibition, Characterization of Minerals, Metals, and Materials*, San Antonio, TX, March 2019.

T. A. Ivanoff, J. D. Madison, J. R. Koepke, and B. H. Jared, "Assessing the Impact of Image Acquisition and Processing Methods on Three-Dimensional Microstructural Reconstructions", *Materials Science & Technology Technical Meeting and Exhibition (MS&T 2018)*, Columbus, OH, October 2018.

T. A. Ivanoff, J. D. Madison, J. R. Koepke, E. Schwaller, B. H. Jared, J. A. Mitchell, and L. P. Swiler, "Three-Dimensional Registration of Part Design, Melt Pool History and Resultant Structure in Additively Manufactured 316L Stainless Steel", *Materials Science & Technology Technical Meeting and Exhibition (MS&T 2018)*, Columbus, OH, October 2018.

T. A. Ivanoff, J. D. Madison, J. R. Koepke, B. H. Jared, J. A. Mitchell, and L. P. Swiler," Three-Dimensional Characterization of Porosity Defects and their Correlation to Mechanical Properties in AM 316L Stainless Steel", *29th Annual International Solid Freeform Fabrication Symposium- An Additive Conference*, Austin, TX, August 2018.

T. A. Ivanoff, T. J. Watt, and E. M. Taleff, "Digital Image Analysis for the Automated Measurement of Dendritic Microstructures in Vacuum Arc Remelted Nickel Alloy 718," *TMS 2018 Annual Meeting & Exhibition*, Phoenix, AZ, March 2018.

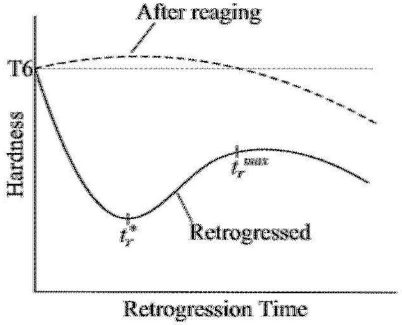
Education

Retrogression-Reaging and Hot Forming of AA7075

- Developed a new forming approach for high-strength aluminum alloy AA7075 for General Motors

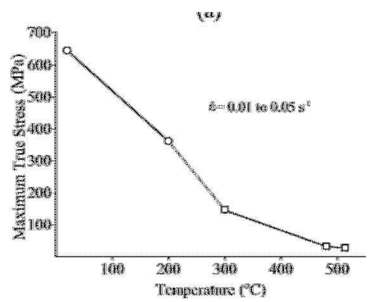
1

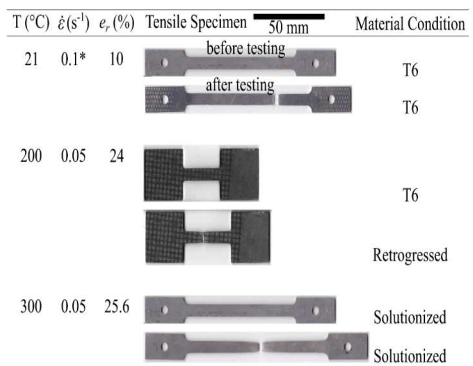
Adapt existing knowledge of RRA treatments to enable new processing technologies



2

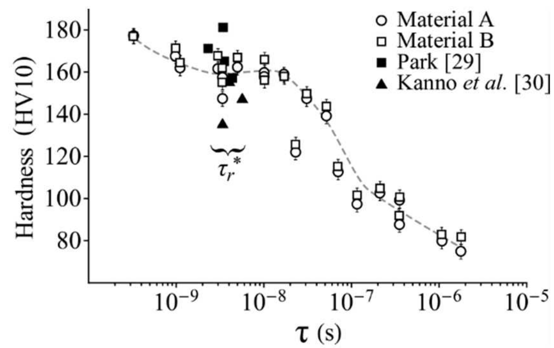
Evaluate mechanical response to treatment and relate to microstructure





3

Relate performance to microstructure



Arrhenius relationship for hardness with temperature-dependent retrogression time using diffusion rate for Zn

Testing on MTS load frames
Simulated forming conditions

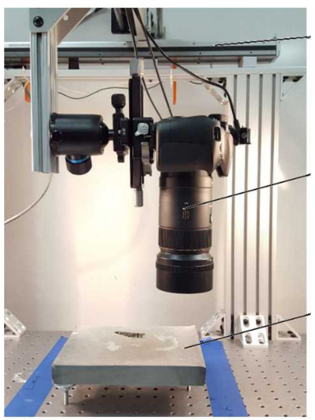
T. A. Ivanoff, J. T. Carter, L. G. Hector, and E. M. Taleff. "Retrogression and Reaging Applied to Warm Forming of High-strength Aluminum Alloy AA7075-T6 Sheet," *Metallurgical and Materials Transactions A*, vol. 50, no. 3, 2019, pp. 1545-1561.

Reconstruction of Solidification History from Cast Microstructure in Remelted Nickel Alloy 718

- Provided data for validation of a Nickel remelting model for AFRL and the LMPC

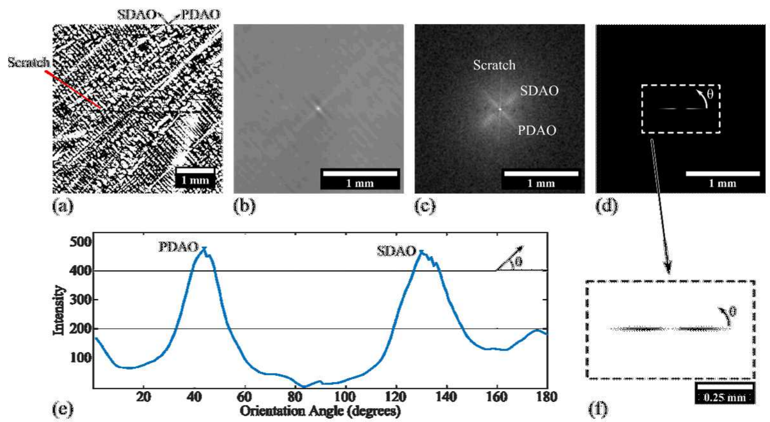
1 → 2 → 3

1 Determined validation data required for model and designed/implemented hardware



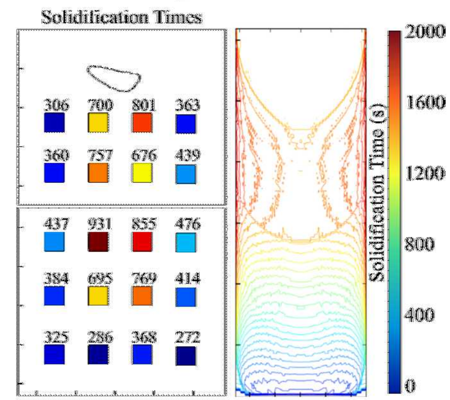
Mentored 2 undergraduates (Katie Adams, Mykal Madrird)

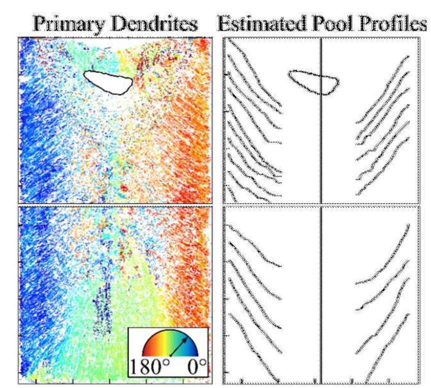
2 Developed automated analysis methods to quantitatively assess microstructures



Two-point correlation function

3 Validate computational models

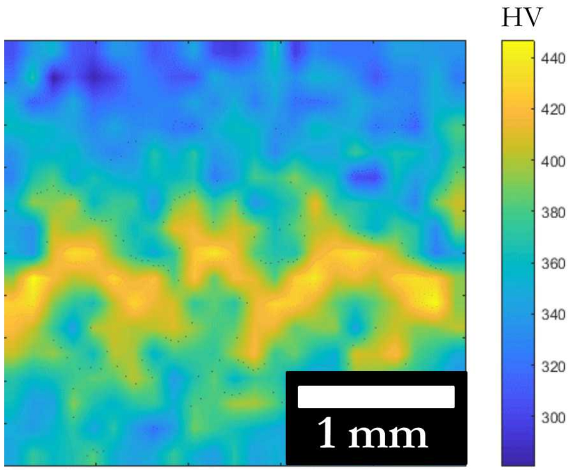




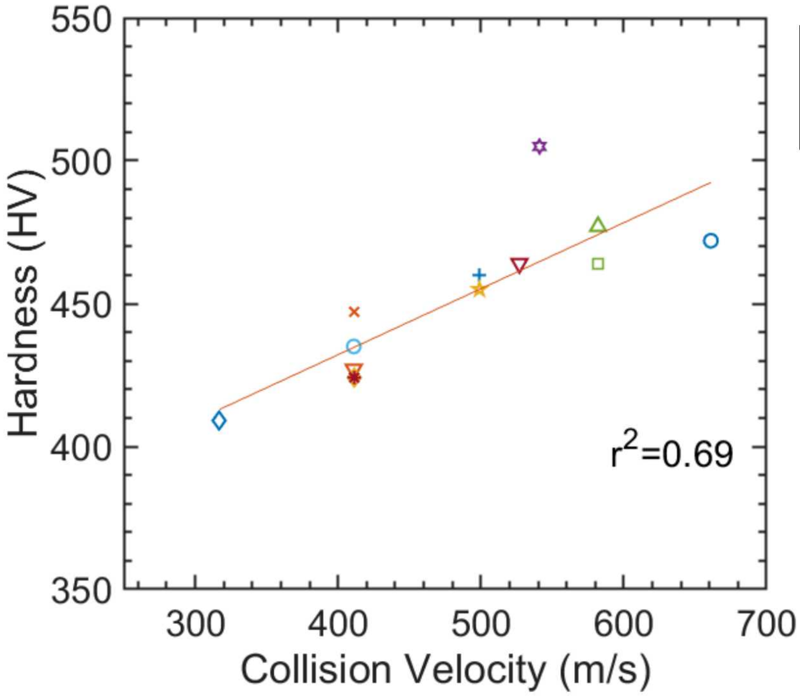
T. A. Ivanoff, T. J. Watt, and E. M. Taleff. "Characterization of Solidification Microstructures in Vacuum Arc Remelted Nickel Alloy 718," *Metallurgical and Materials Transactions B*, vol. 50, no. 2, 2019, pp. 700-715.

Vickers Microhardness

Study local hardness variation across the bond interface and into the parent material

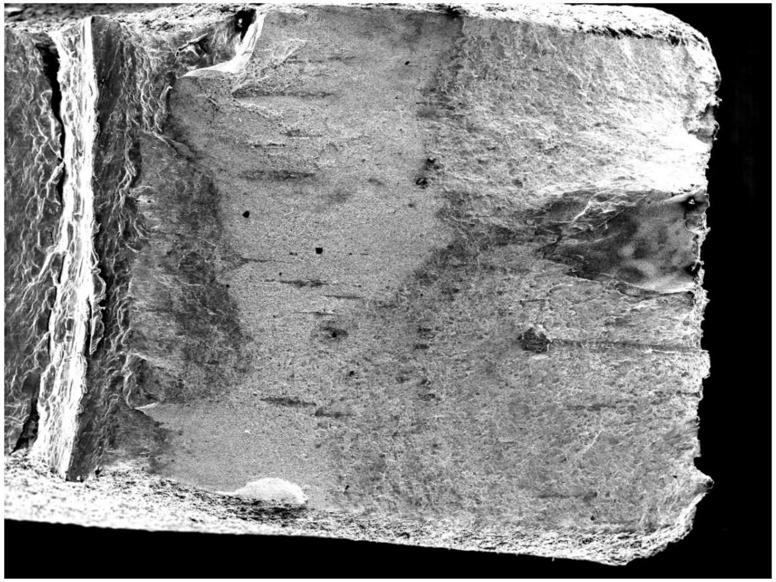


Relate peak hardness to processing parameters:

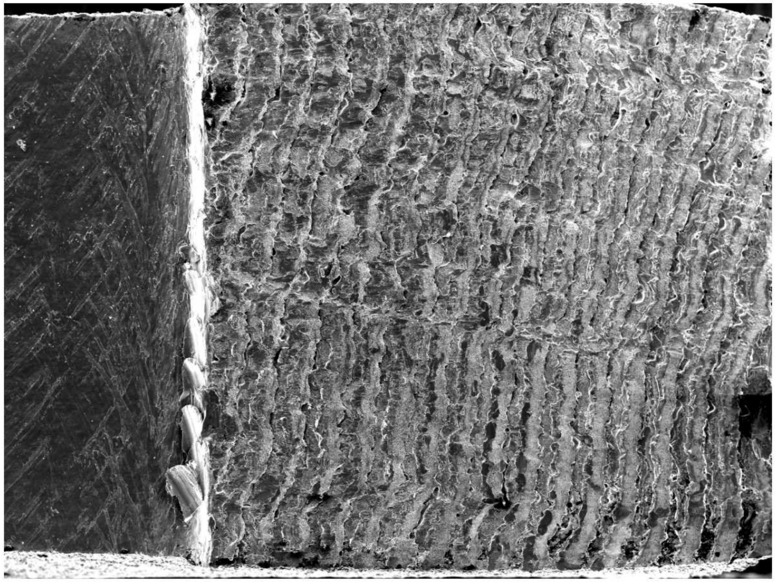


Hardness demonstrates a relationship with collision velocity

Explosive Bonding Full Area SEM

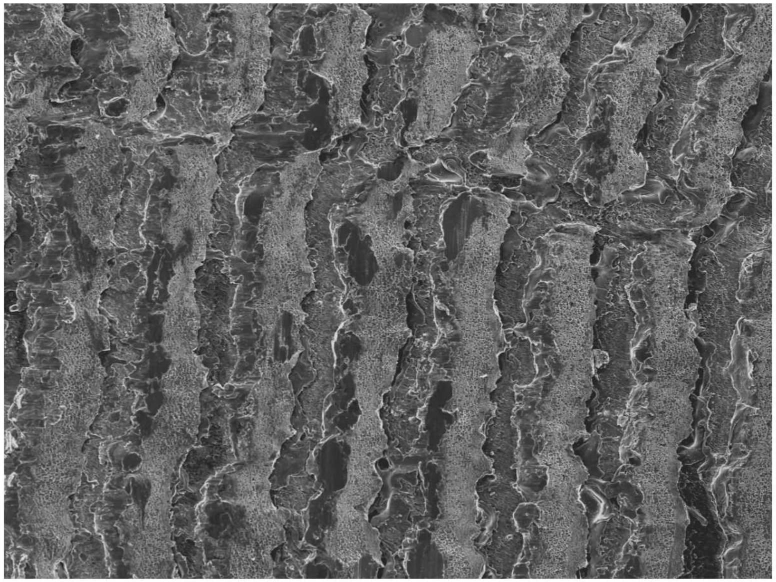


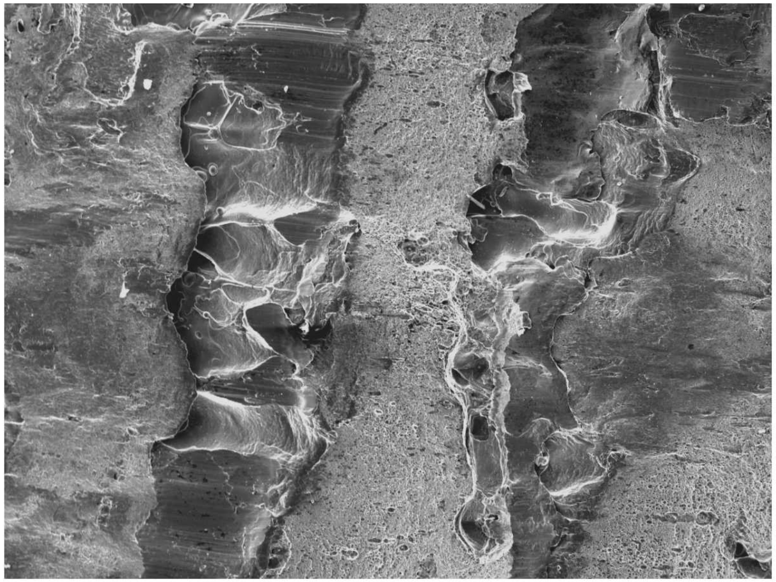
SEM image #4
SSP10-4 (highest performer) 100.6 ksi
-failed in parent material (mostly shear) 1540 lbs.



SEM image #2
SSP9-4 (highest performer) 68.6 ksi
-failed along interface 1050 lbs.

FOV: 1.422x1.067
mm

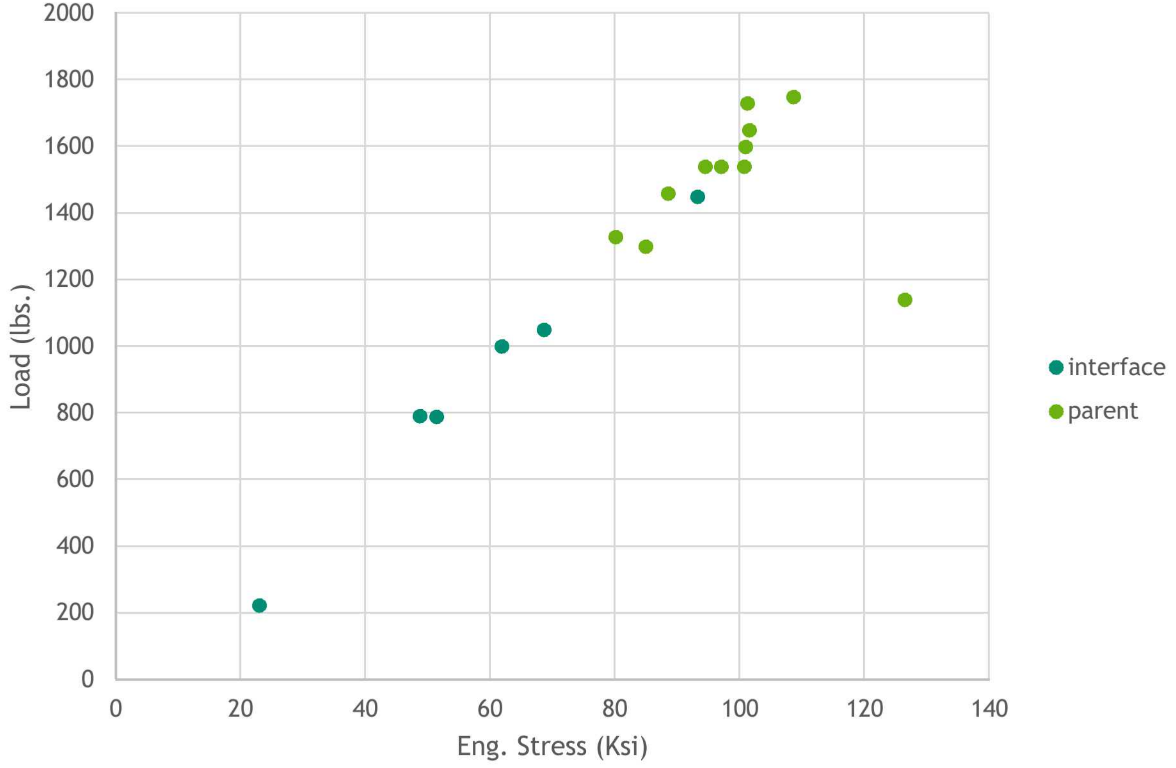




SEM image #19 (X003,Y003)
SSP9-4 (highest performer)
-failed along interface

SEM image #33 (X003,Y001)
SSP40-3 (lowest performer)
-failed along interface

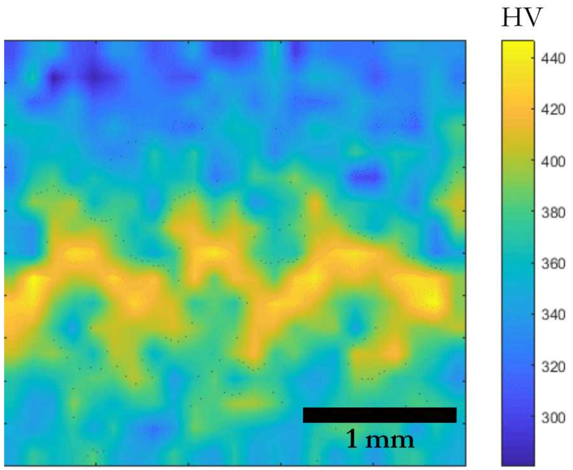
Explosive Bonding Load vs Engineering Stress



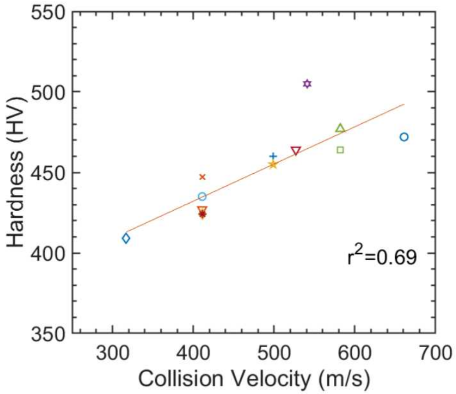
Vickers Microhardness

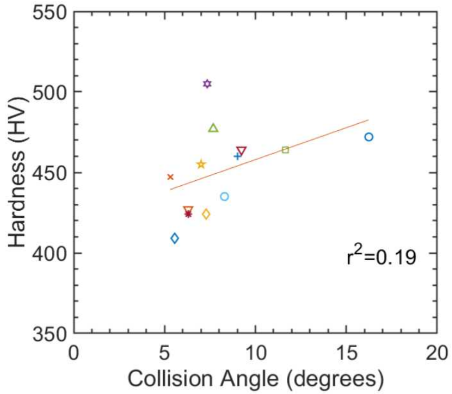
Microhardness provides greater spatial fidelity compared to lap-shear test

- Study local hardness variation across the bond interface and into the parent material

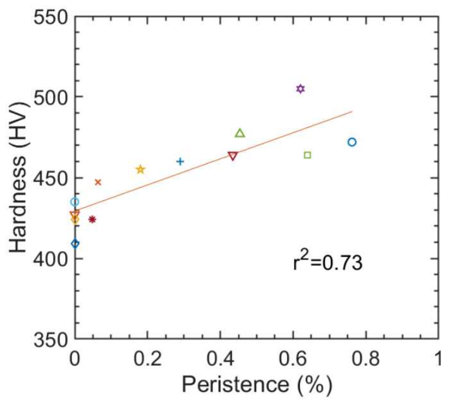


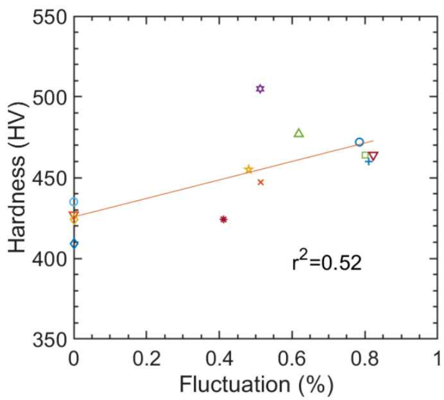
Relate peak hardness to interface parameters:

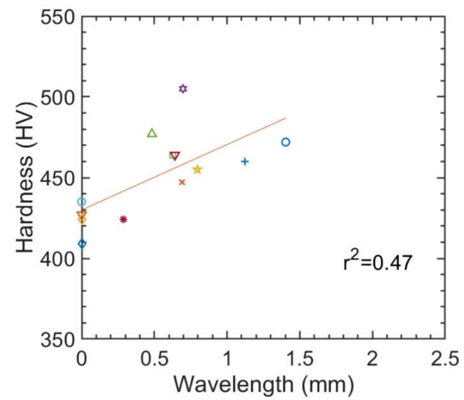




Hardness shows a relationship with collision velocity and persistence



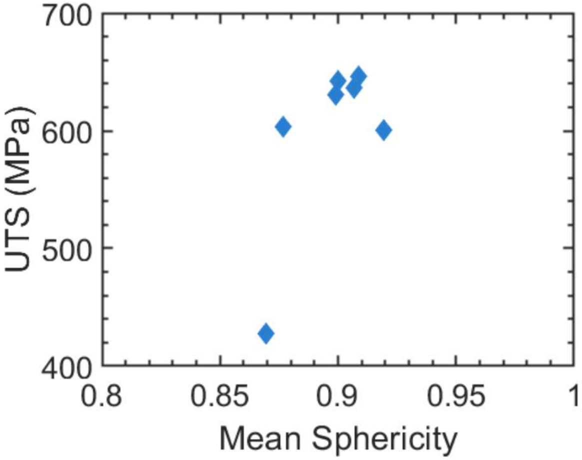


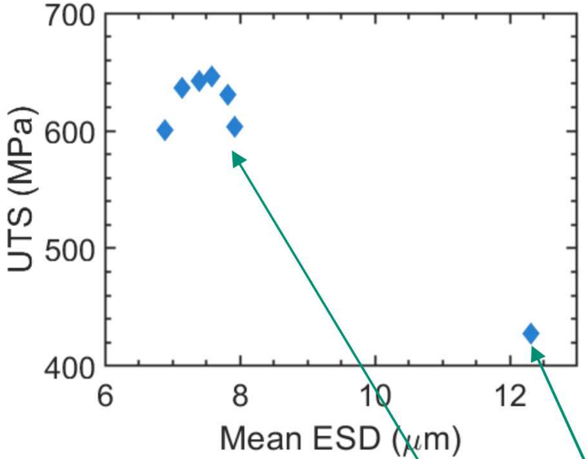


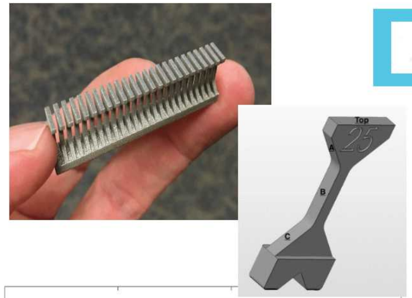
AM Defect Quantification

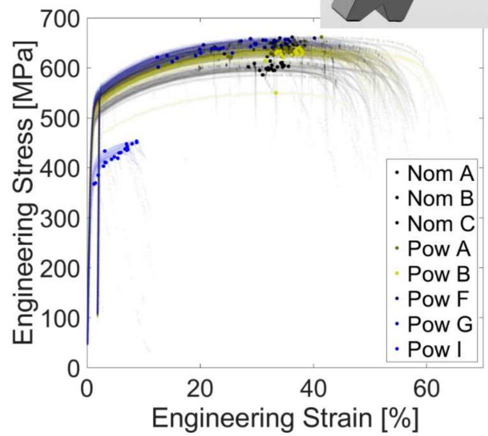
Prior work yet to discriminate high-correlation links between fine-scale changes in performance and porosity

- No trend between volume aggregate pore measures and fine-scale mechanical performance



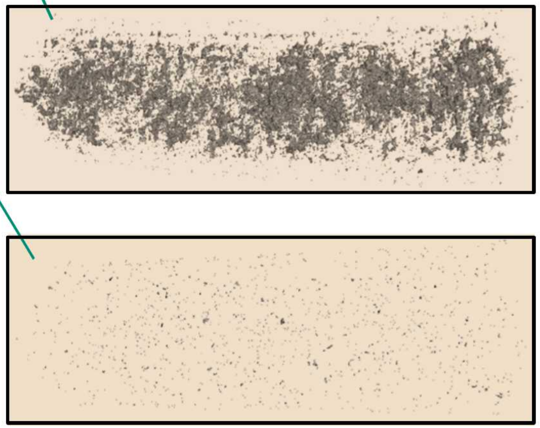






Nathan Heckman et al.

Wilson-Heid et al. found that UTS and elongation to failure affected when pore diameter reaches 16% and 9% of the cross-sectional area of fabricated cylinders

3D Porosity	Density
	90% ≥95%

Wilson-Heid, A., Novak, T., Beese, A.M.: Characterization of the effects of internal pores on tensile properties of additively manufactured austenitic stainless steel 316l. Experimental Mechanics pp. 1–12 (2018)