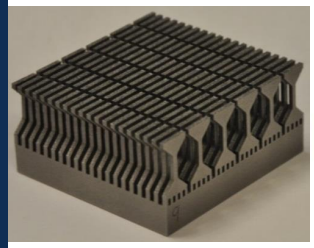
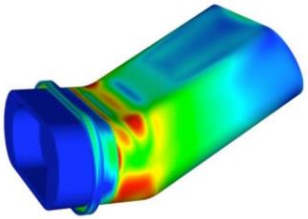
SAND2017-2836C

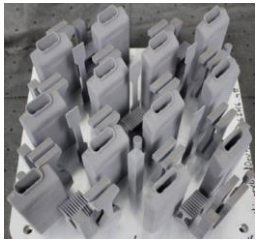
Material Assurance for AM Metal Components

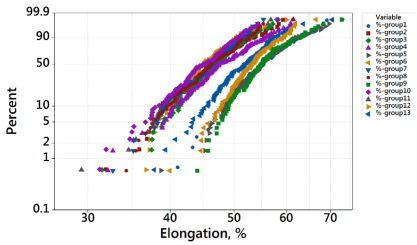
Bradley Jared, PhD

Materials Science & Engineering









Sandia National Laboratories

Exceptional service in the national interest

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

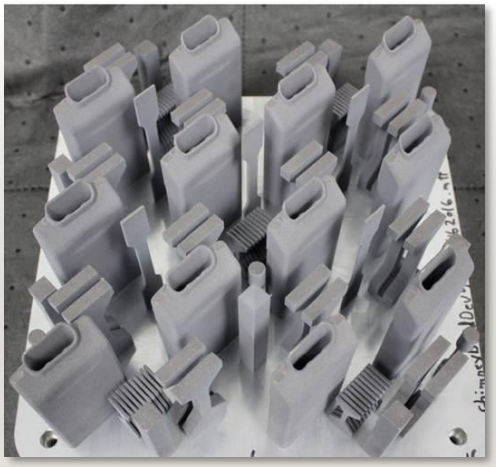
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 20161-XXXXP

Outline

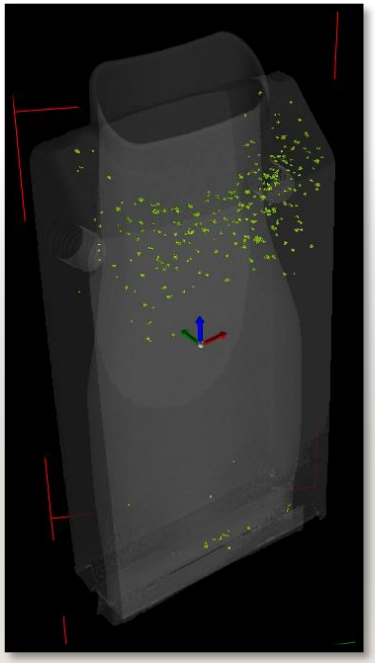
- Material assurance
  - qualification today
- AM defects
  - quantifying material distributions
  - defect signatures
  - process development
- Qualification tomorrow

Material Assurance

- Material formation concurrent w/geometry
  - how to ID a bad part?
    - must quantify critical defects & useful "signatures"
    - processes are currently open loop
    - complexity isn't "free"
  - requires significant design margins **and/or** rigorous post-process inspection / validation

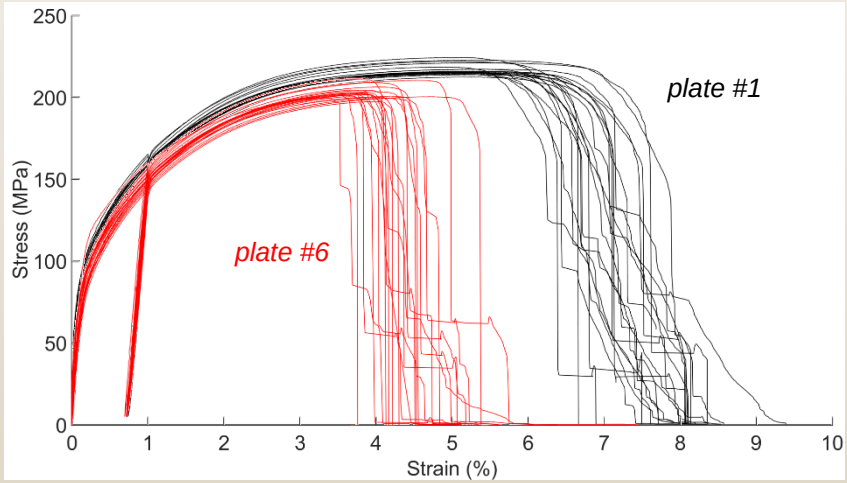


development build plate



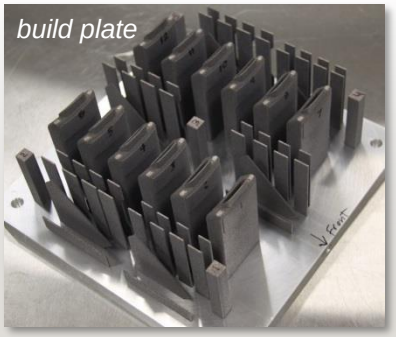
porosity via CT

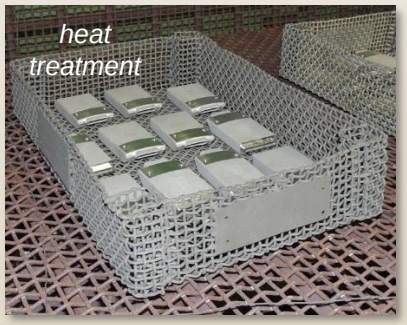
- Point qualification today
  - development
    - same phase gate process, still test parts & materials
    - develop & evaluate "new" materials
    - must establish property distributions w/probabilities & worst case, not just mean
  - production
    - product acceptance is greatest challenge
      - destructive sampling (random part per plate)
      - test artifacts (tensile, Charpy, density, composition, powder, ???)
      - inspection (CT, dimensional, powder)
    - DA & PA working closely together on requirements, specifications & methods



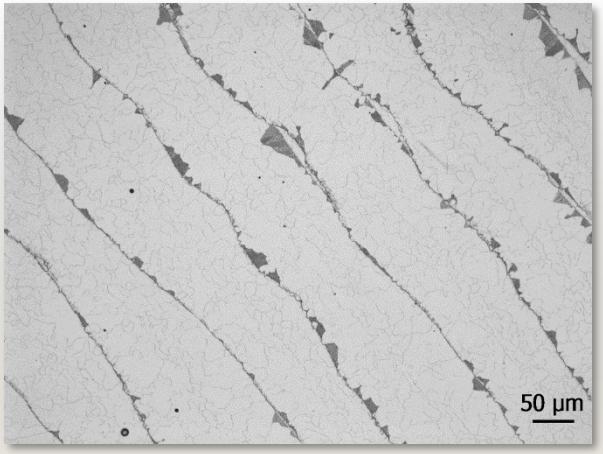
HTT curves for development build plates #1 & #6

Process Development

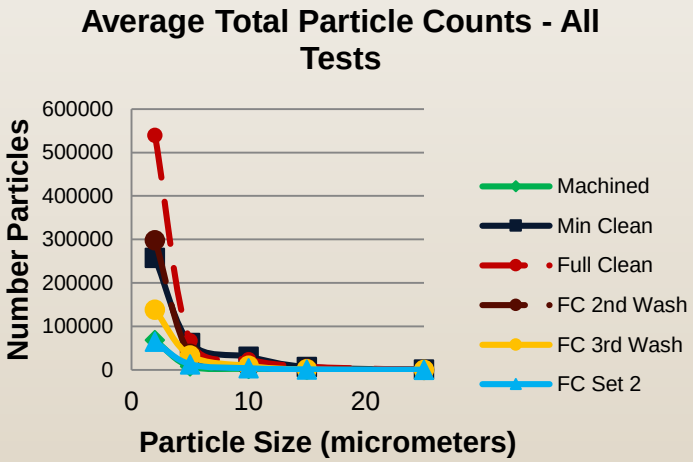




production process development w/KCNSC

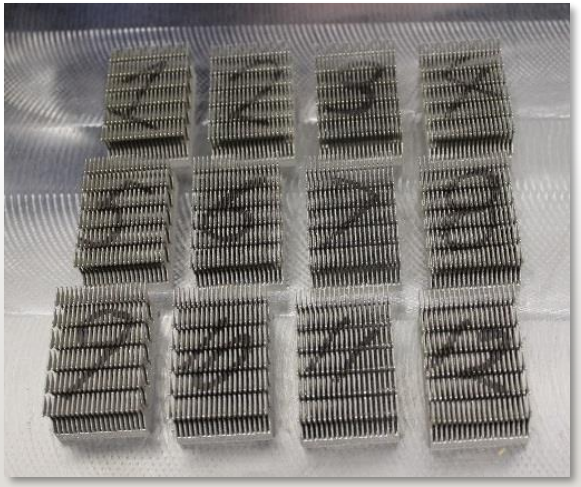


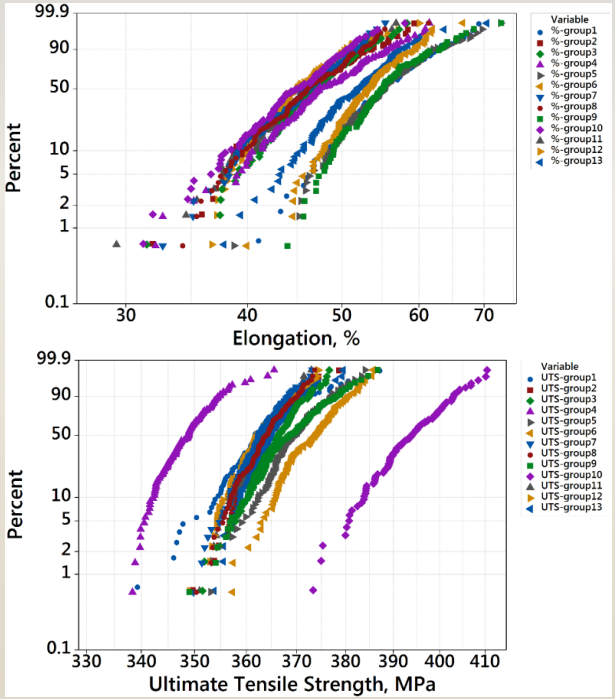
crack resistant 304L microstructure from weld critical powder



increased cleaning time (light blue) reduces loose 304L particle count to machined housing levels (green)

HTT array design w/120 tensile bars for 304L process sensitivity study



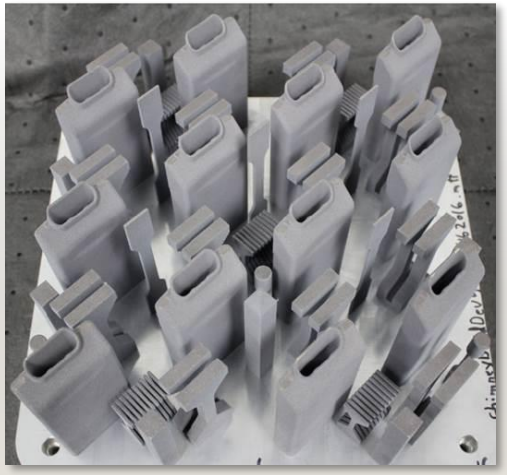


304L performance over 13 different process settings, >1500 tensile tests represented

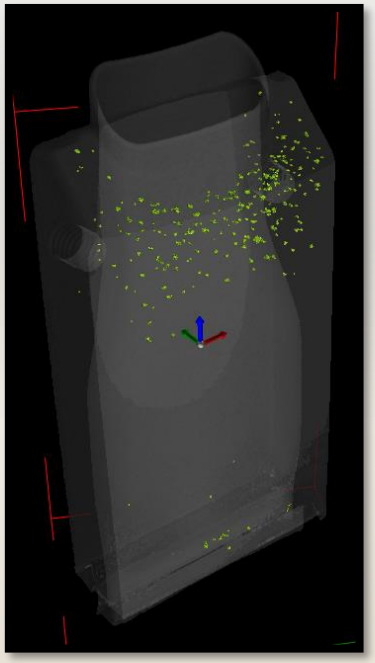
Clint Holtey, Lisa Deibler, Jay Carroll, Bradley Jared

Jeff Rodelas, David Bonner

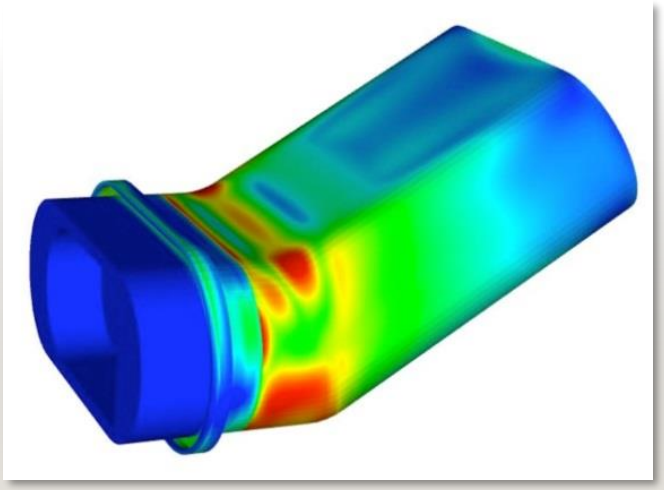
Product Requirements



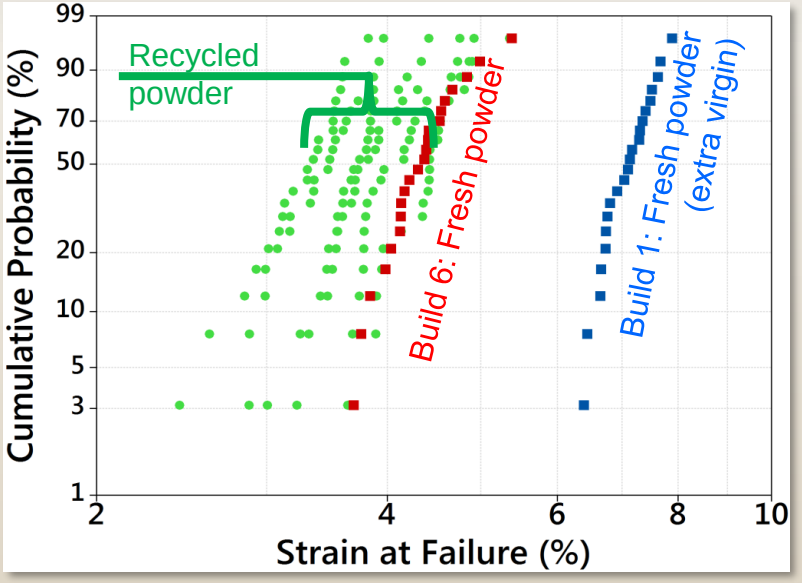
development build plate



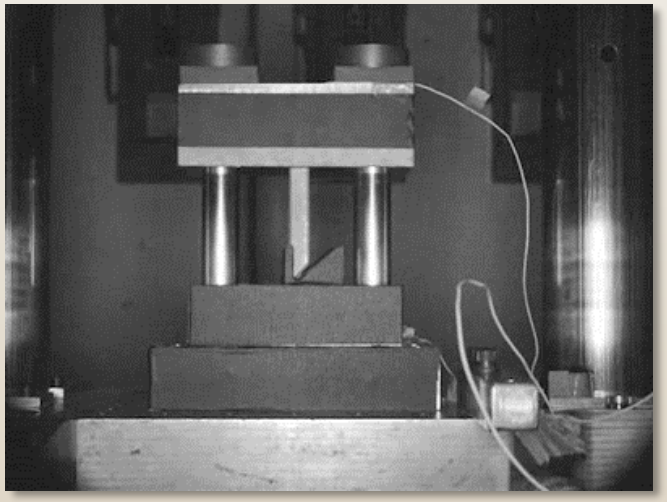
porosity via KCNSC CT



stress contours for a z-direction high-frequency flight shock excitation



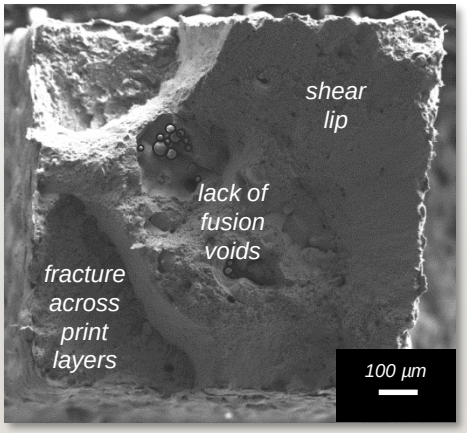
Al10SiMg development build large HTT stress-strain curves



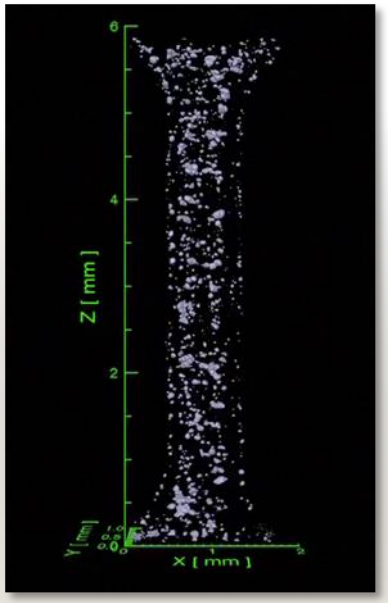
axial impact test

Quantifying Critical Defects

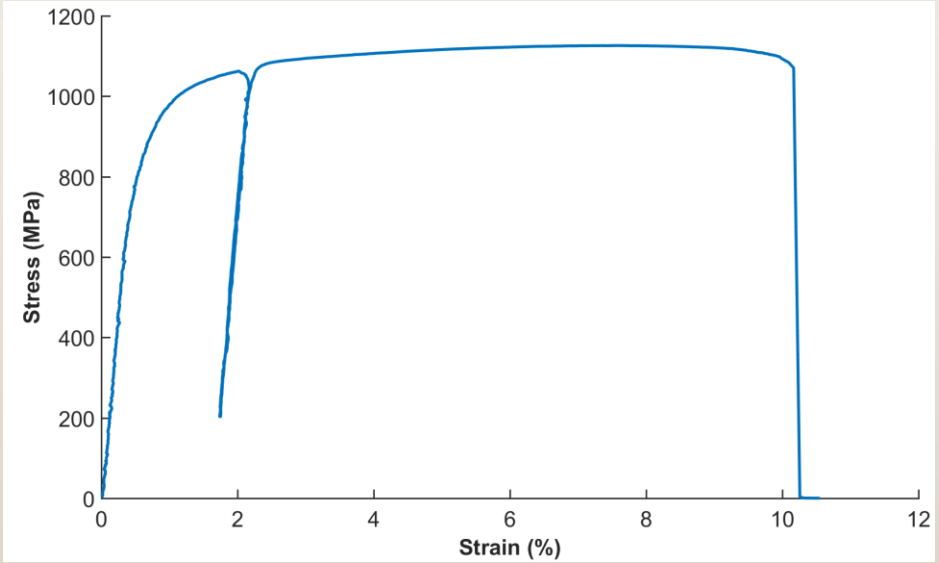
- Characterize, predict & control for laser PBF
  - exploring precipitation hardened SS as alternate to 304L
  - higher strength w/multiple strengthening mechanisms
- Understand mechanistic impacts on properties
  - build process-structure-property relationships to predict margins & reliability
  - characterize stochastics
  - design for uncertainties
  - provide scientific basis for qualification



17-4PH dogbone fracture surface



17-4PH dogbone porosity

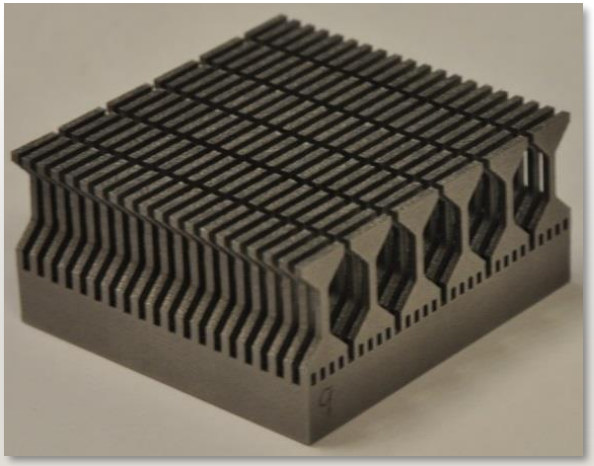


17-4PH dogbone stress strain response

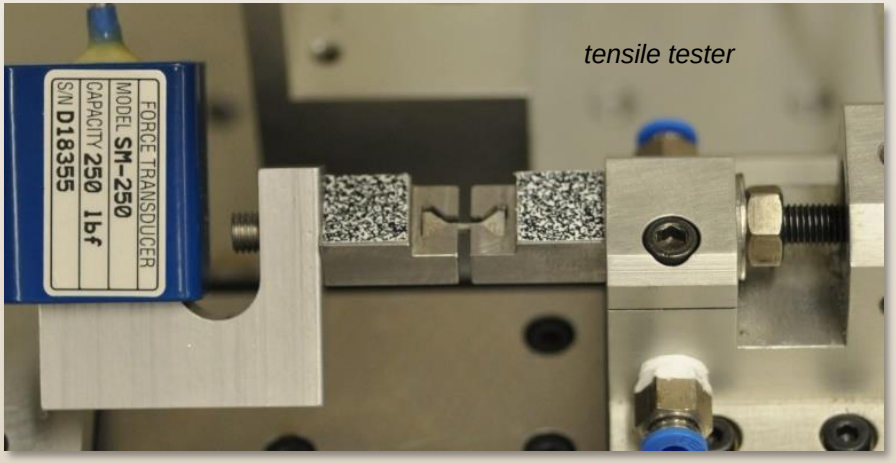
Bradley Jared, Brad Boyce, Jeff Rodelas, Jon Madison, Brad Salzbrenner, Laura Swiler, Jacob Ostien, Olivia Underwood, Chris Stork

High Throughput Tensile Testing

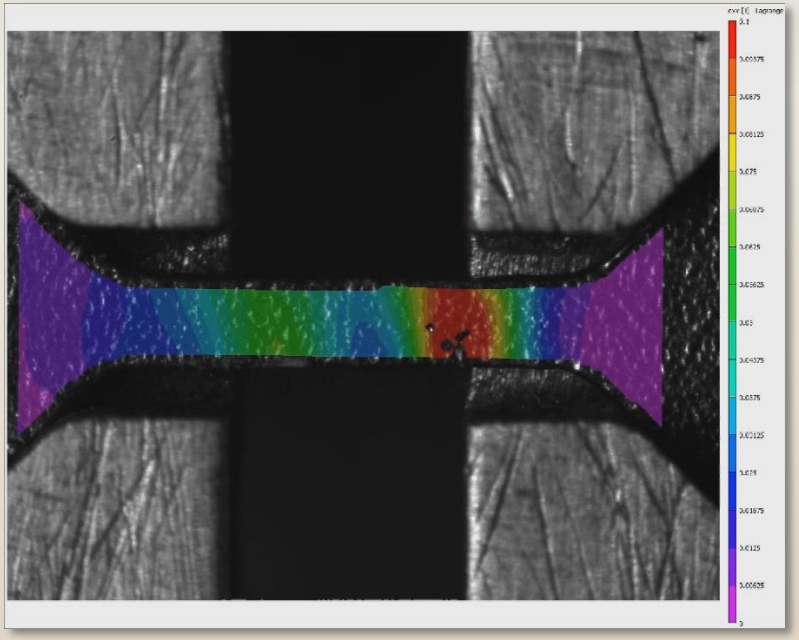
- Characterizing material distributions & process-performance relationships
  - requires rapid performance quantification
  - custom dogbone per ASTM
  - digital image correlation (DIC)
  - exploring heat treatment, feature size, build orientation, HIP & process parameters



high throughput test sample w/120 dogbones, 1x1mm gage x-section



tensile tester

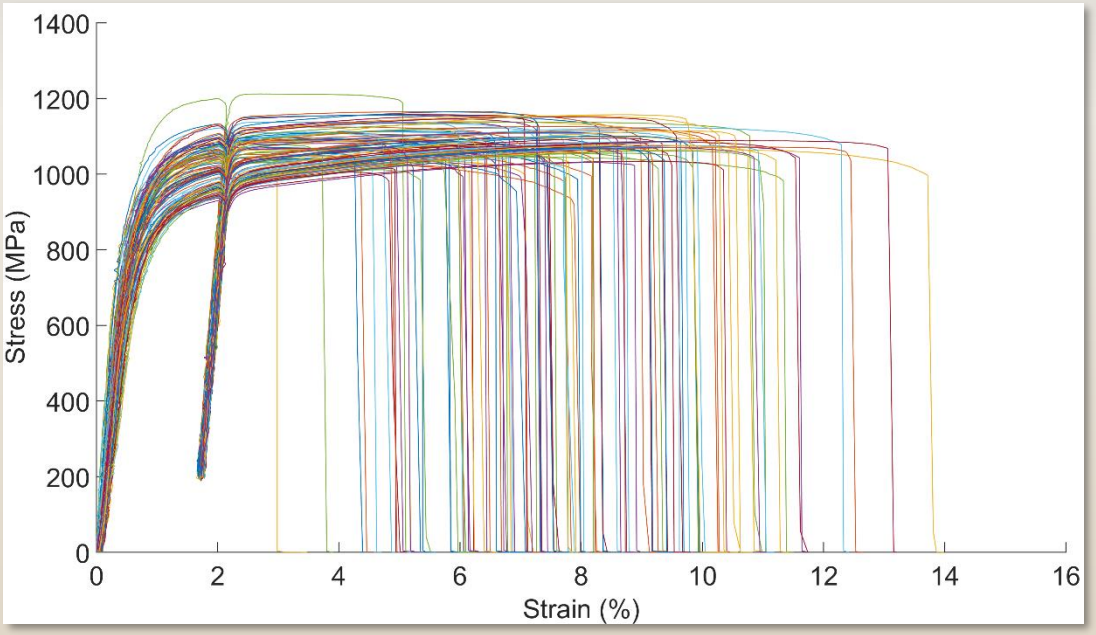


tensile test w/DIC strain field overlay

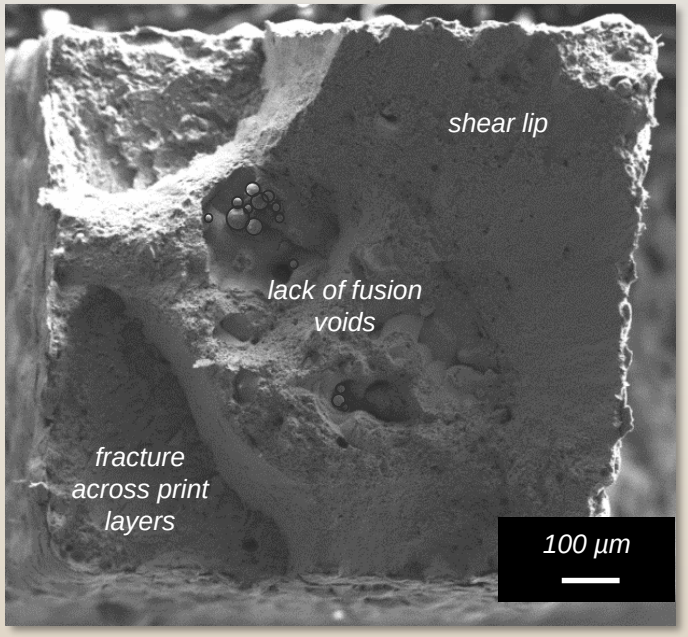
Salzbrenner, B., Journal of Materials Processing Technology, 2017

Stochastic Stress-Strain Response

- Quantifying mean, outliers & probabilities
- Defect dominated failure
  - limited area reduction
  - observe ductile dimples & shear rupture planes
  - voids & lack-of-fusion boundaries are likely crack nucleation sites
  - similar to castings & ceramics



110 stress-strain curves for 17-4 PH after SHT+H900 for correlation study



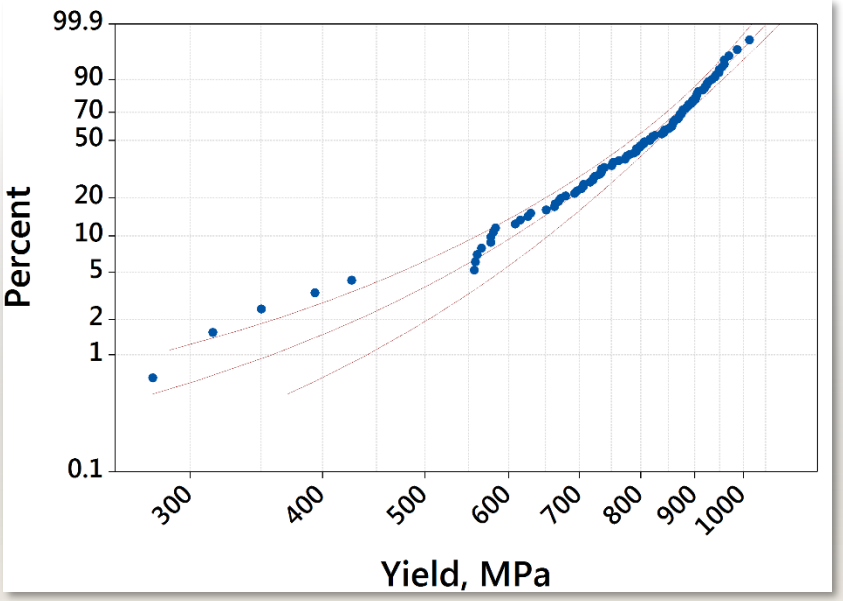
failure at 2% elongation, SHT+H900

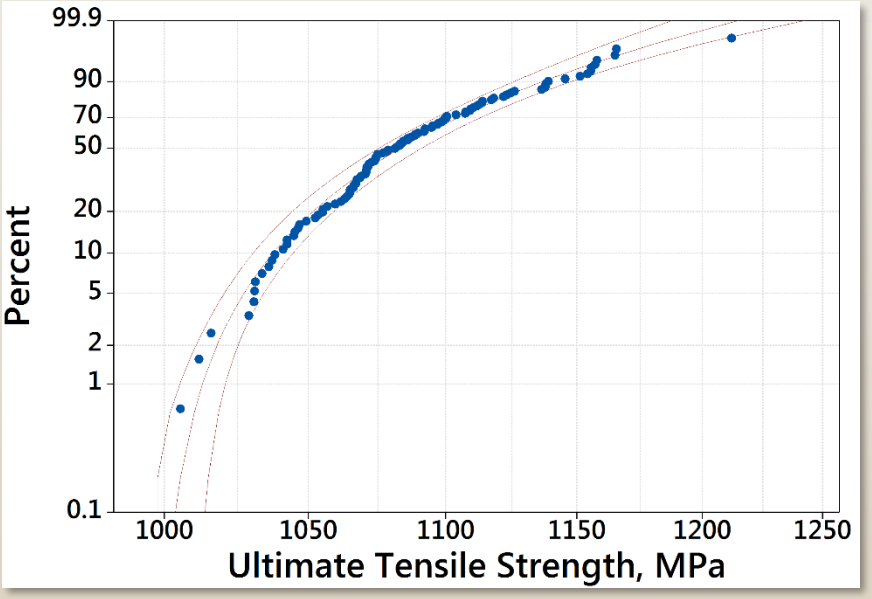
Material Performance Fit to 3-Parameter Weibull Distributions

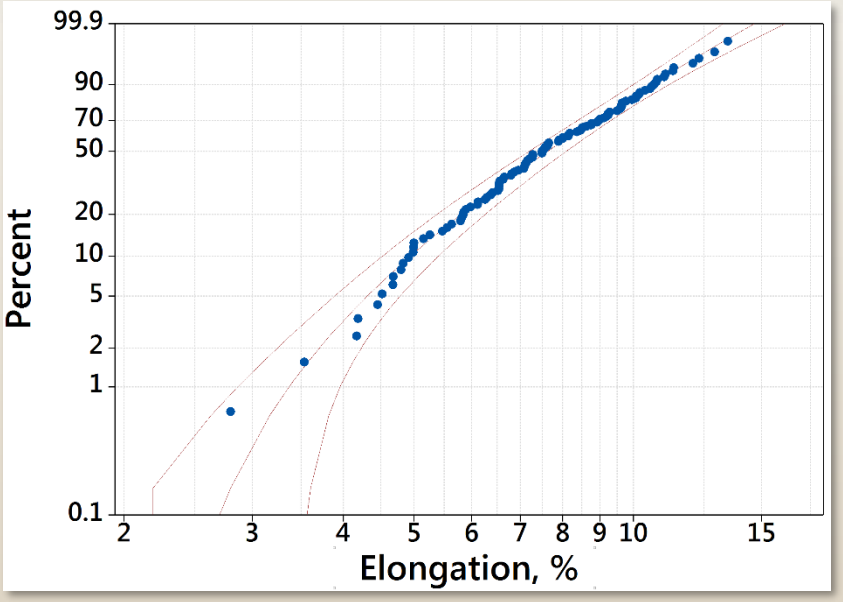
- Based on weakest link theory

$$P = 1 - \exp\left[-\left(\frac{\sigma - \sigma_0}{\sigma_\theta - \sigma_0}\right)^m\right]$$

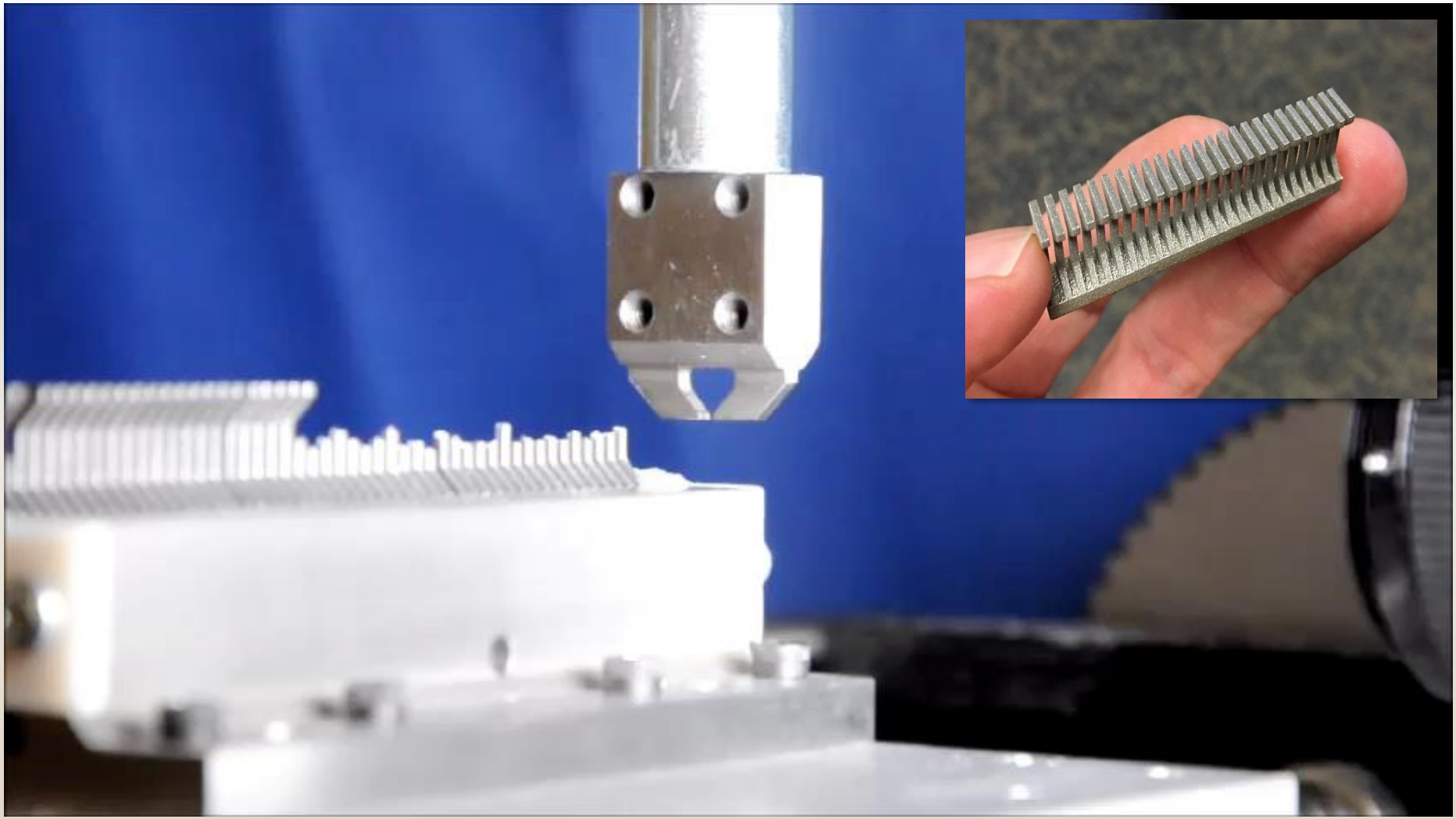
- where
  - P = probability of failure at stress, σ
  - m = Weibull modulus, i.e. scatter
  - σ_θ = characteristic strength
  - σ_o = threshold, strength where P = 0





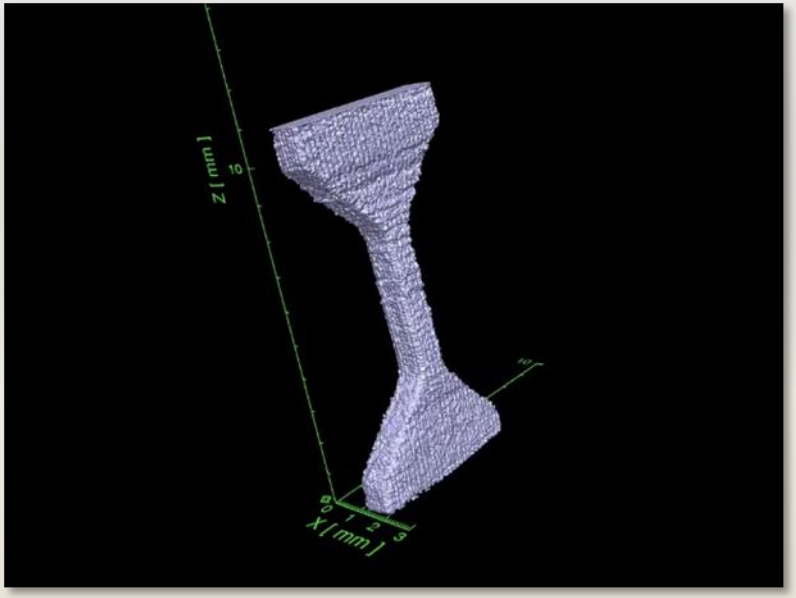


Gen 2



Exploring Defect Signatures

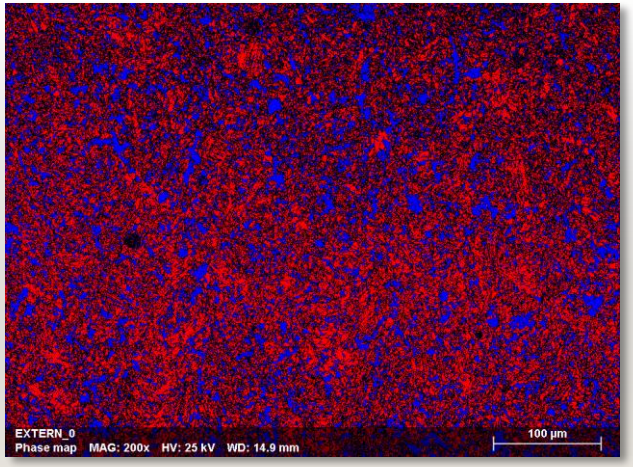
- Examining multiple techniques
  - destructive
    - high throughput testing (HTT), fractography, metallography, serial sectioning
  - non-destructive
    - computed tomography (CT), density, resonant ultrasound spectroscopy (RUS)
  - what can we ID accurately & efficiently?
- Correlation study
  - data sets for 110 17-4PH samples
  - parts from a single baseplate
    - nominally constant process parameters



CT model of 1x1 mm test sample

Metallurgical Interrogations

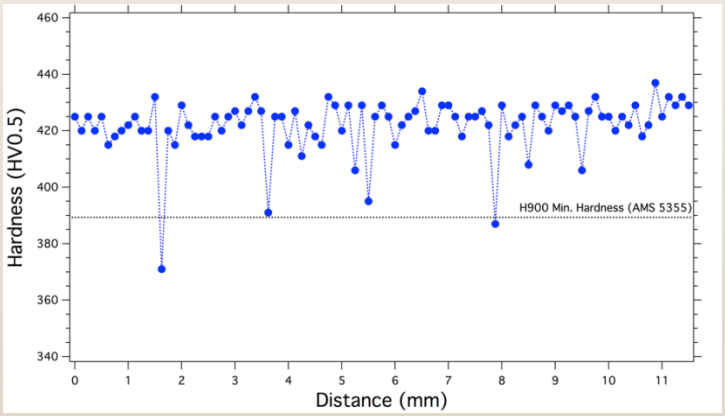
- Microstructure
  - optical, SEM, EBSD, WDS micro-probe
- Composition
  - LECO combustion, ICP mass-spec, XRD
  - powder analysis
- Microhardness



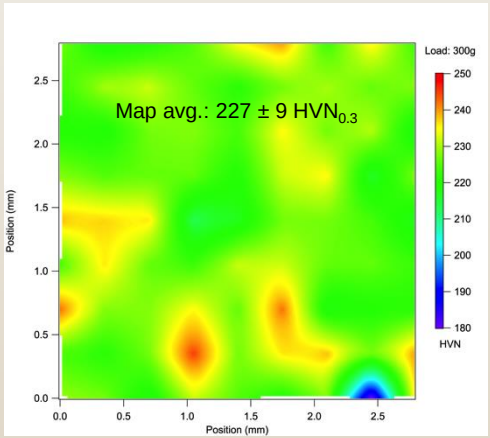
EBSD phase map, SHT+H900, 22% retained austenite

Element	Vendor 1, run 2 (wt%)
Cr	16.64
Mo	0.045
Si	0.38
Nb	0.3
V	0
W	0
Ti	0
Ta	0
Al	0
Ni	4.24
Mn	0.24
C	0.012
N	0.056
Co	0
Cu	4.05
P	0.019
S	0.003
O	0.100
Nb	0.30

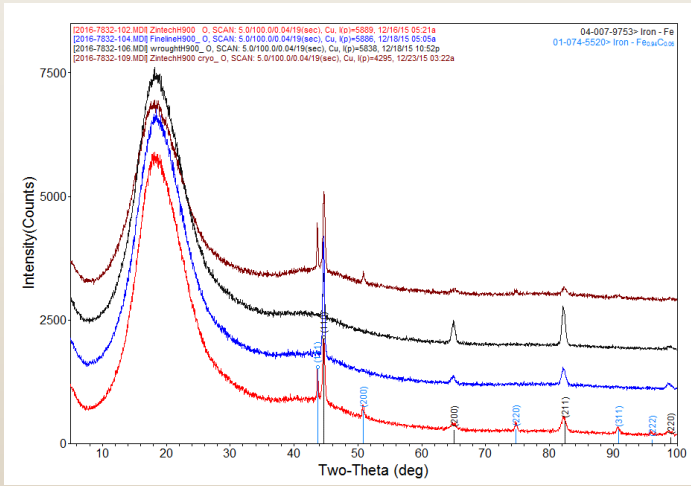
bulk chemical analysis



SHT+H900 microhardness along dogbone length



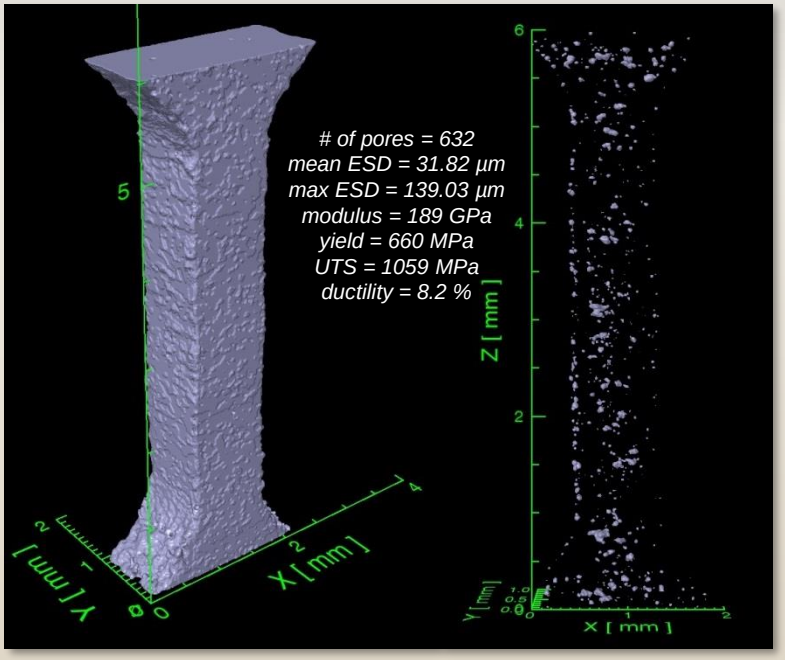
as-printed microhardness on gauge cross section



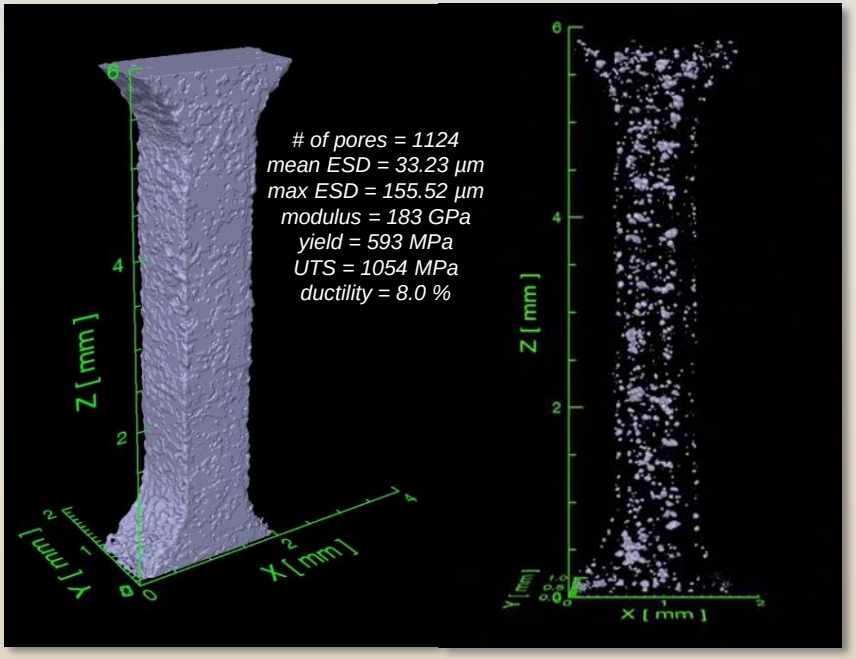
bulk XRD analysis

Computed Tomography

- Dogbones
  - gage sections imaged w/resolution of 7 or 10 µm voxel edge length
- Quantifying defect distributions
  - what can we see? does it inform material behavior predictions?
    - is CT justifiable for qualification and/or production?
  - comparing w/serial sectioning, density (via Archimedes)



dogbone B,16 CT surface image (left), porosity map (right)

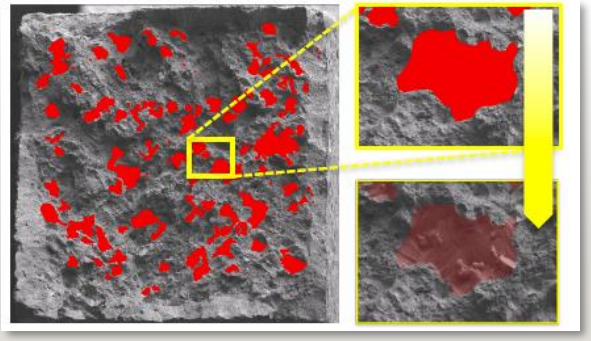


dogbone C,16 CT surface image (left), porosity map (right)

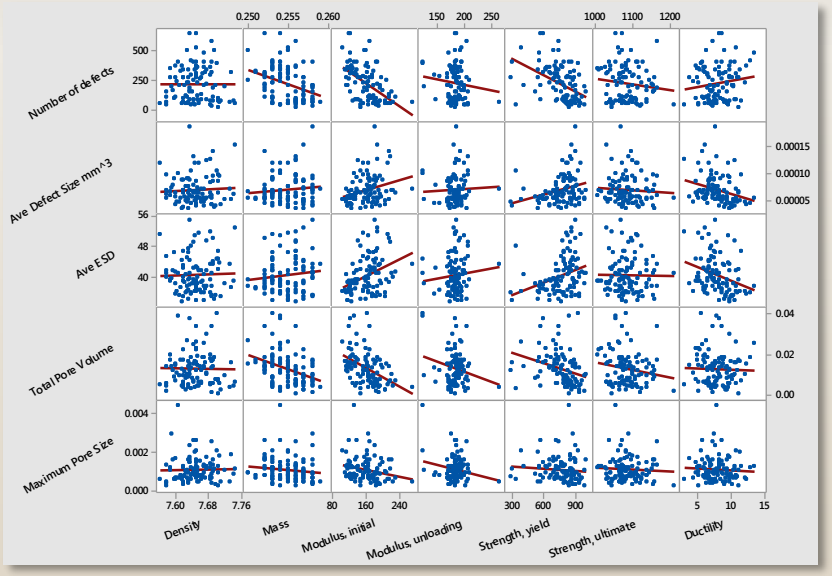
ESD = equivalent spherical diameter

Data Trends Has Been Elusive

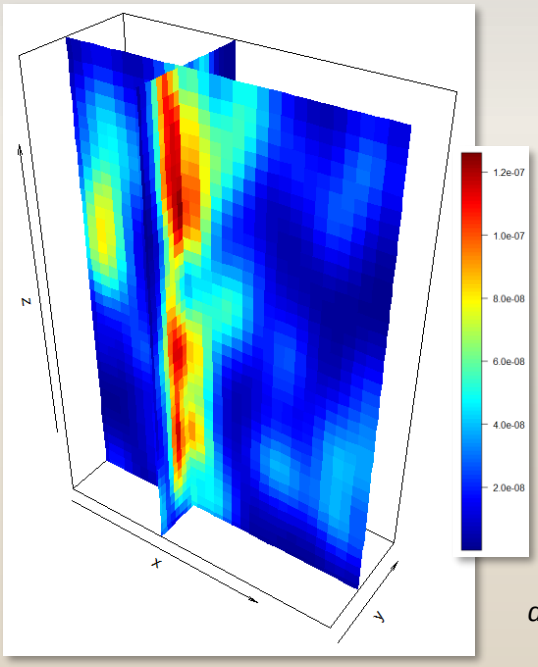
- Tools
  - scatter plots, cluster analysis, PCA, spatial correlations, area fractions, FEA
- Metrics
  - defect size, number, volume, density, void fractions
- Current effort exploring fractography, CT & FEA relationships



fracture surface w/highlighted void fractions



scatter-plot analysis summary

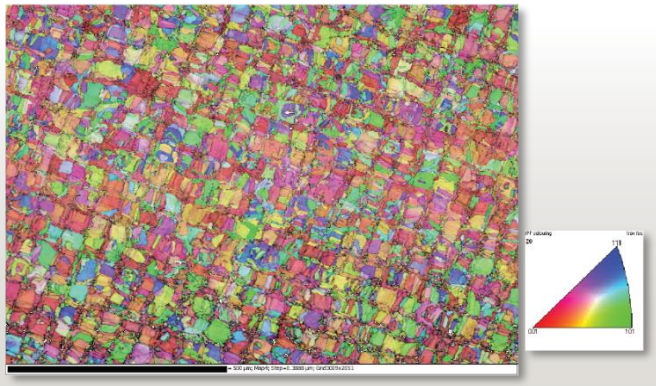


kernel density estimation slice representation

discretization & mesh of defect structure in dogbone A,16 gage section

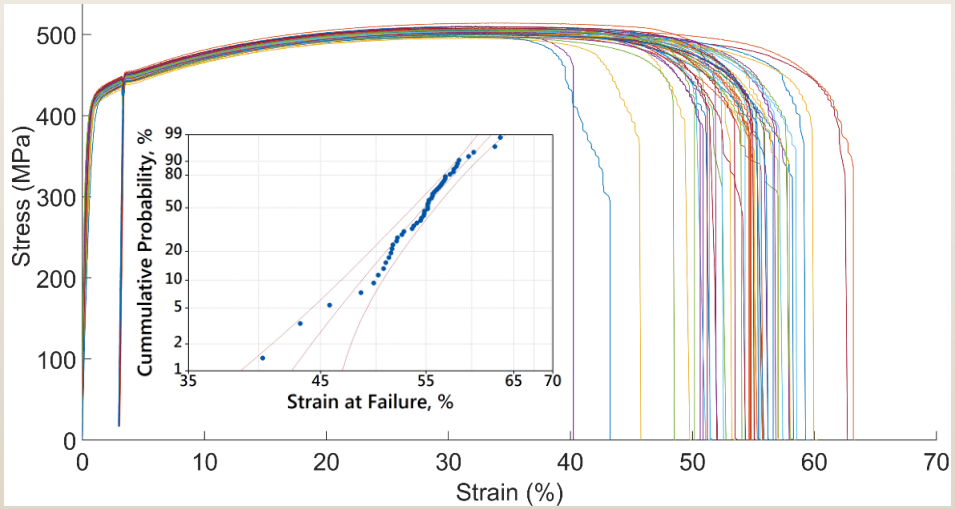
Process Development

- Laser powder bed fusion
  - 3D Systems ProX 200
    - FEI Aspex
  - process mapping w/CMU
  - process sensitivity study
  - process diagnostics
    - Open Protocol
    - in-situ signatures

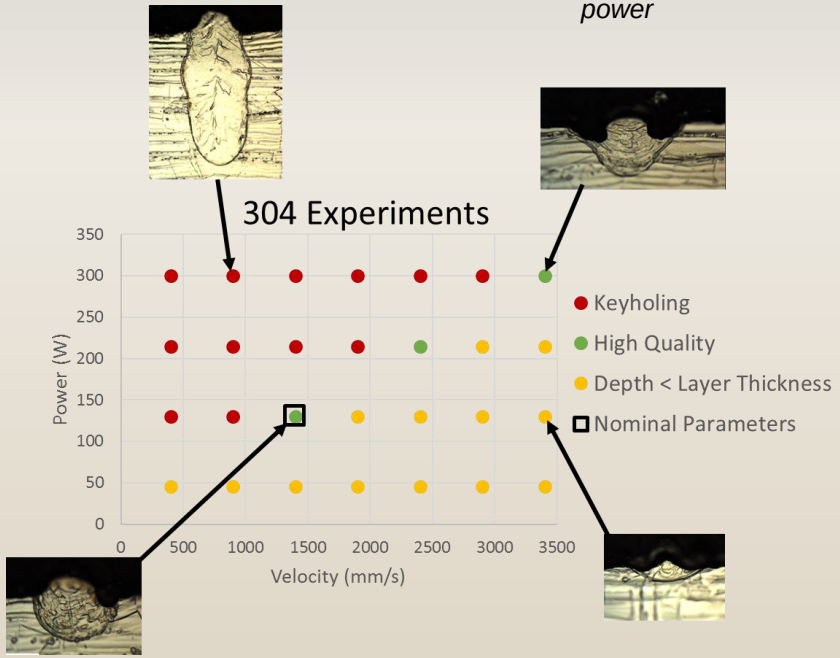


unique EBSD grain structure for 316L SS

Gen 2 samples w/varying laser power

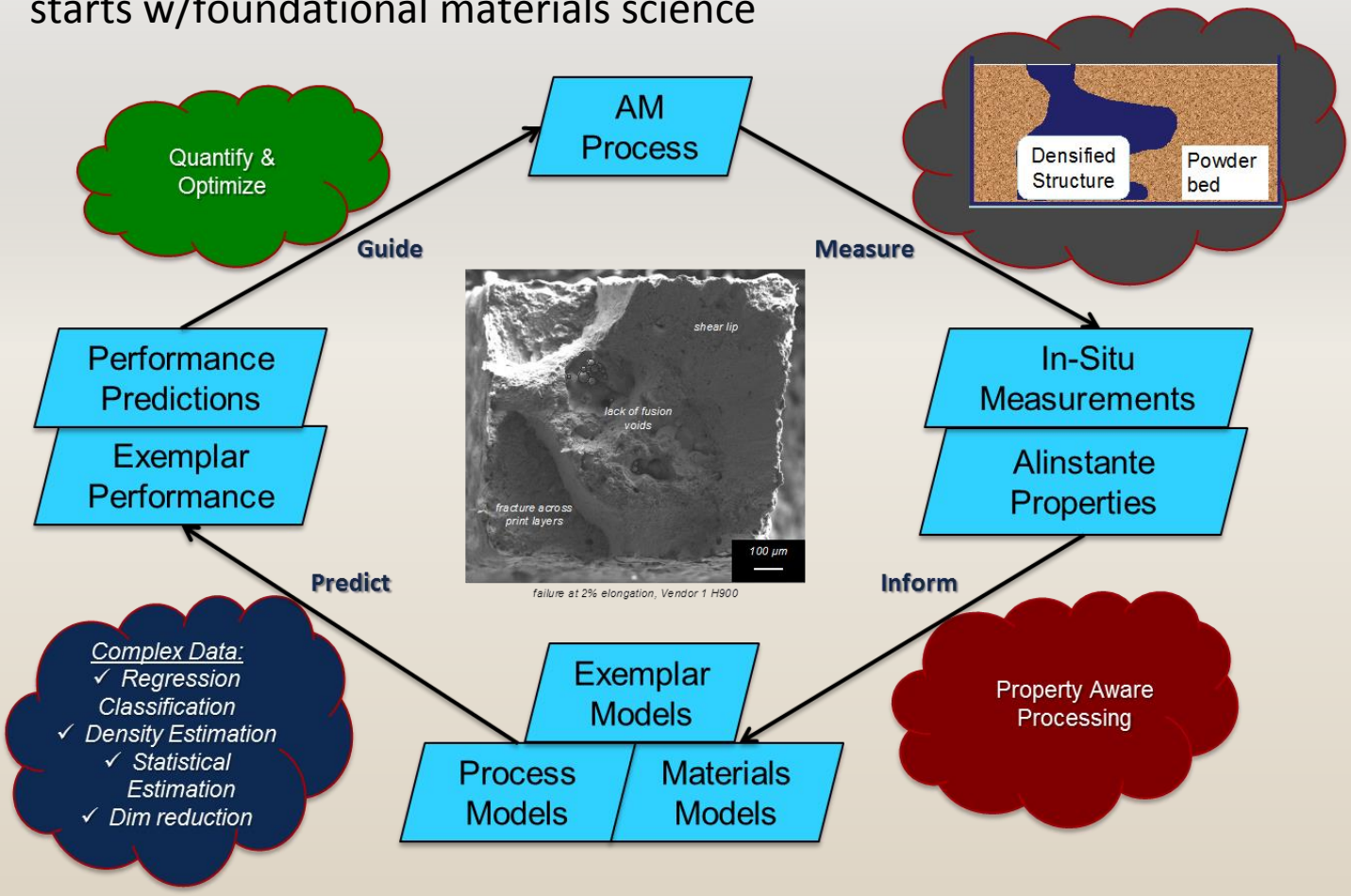


HTT 316L SS data, 50 1x1mm dogbone samples

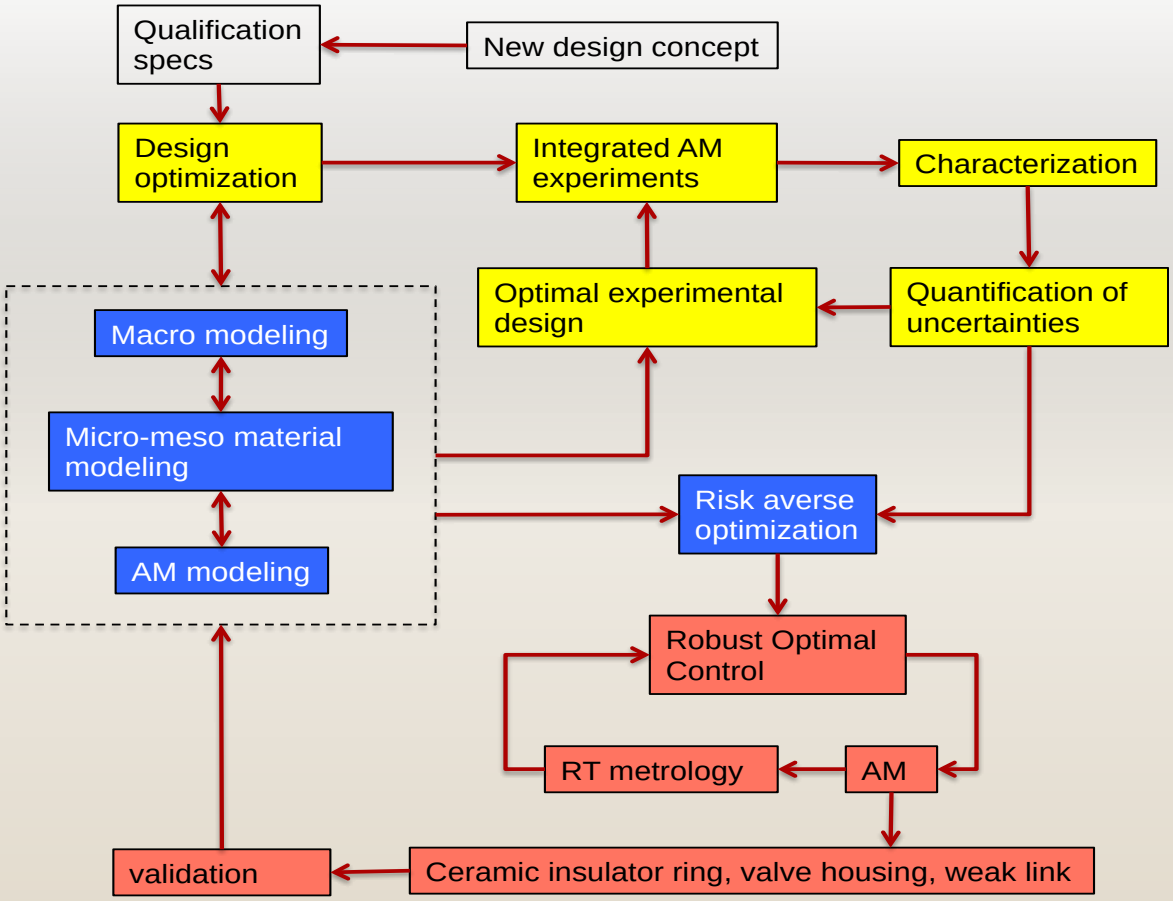


Qualification Tomorrow

- "Changing the Engineering Design & Qualification Paradigm"
  - leverage AM, in-process metrology & HPC to revolutionize product realization
  - starts w/foundational materials science

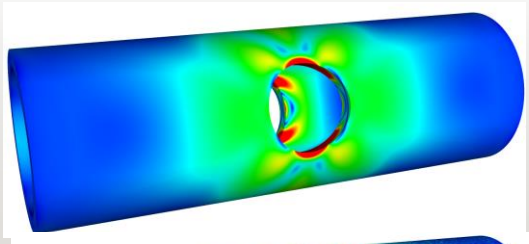


Born Qualified



optimization driven performance

Multiscale Material Modeling



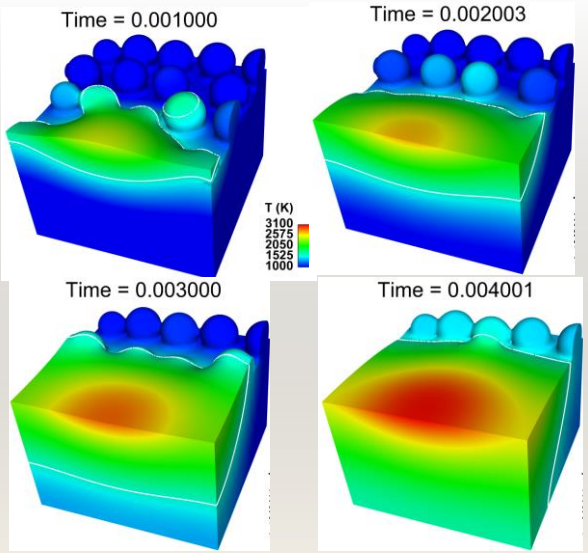
Type 1 residual stress field

Type 2 residual stress field

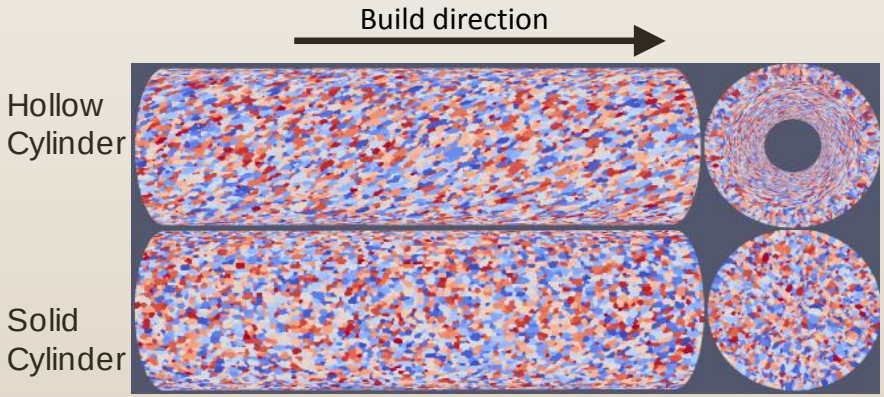
(304L tube loaded in tension through plastic deformation and then unloaded)

residual stress models

3D Power Bed
50 micron 304L stainless
Laser: CW Gaussian
20 W; 200 micron diam
1 cm/s scan rate



SLM simulation of 3D powder bed, illustrating impact of capillary forces on melt dynamics powder and of line-of-sight shading (LOSS)



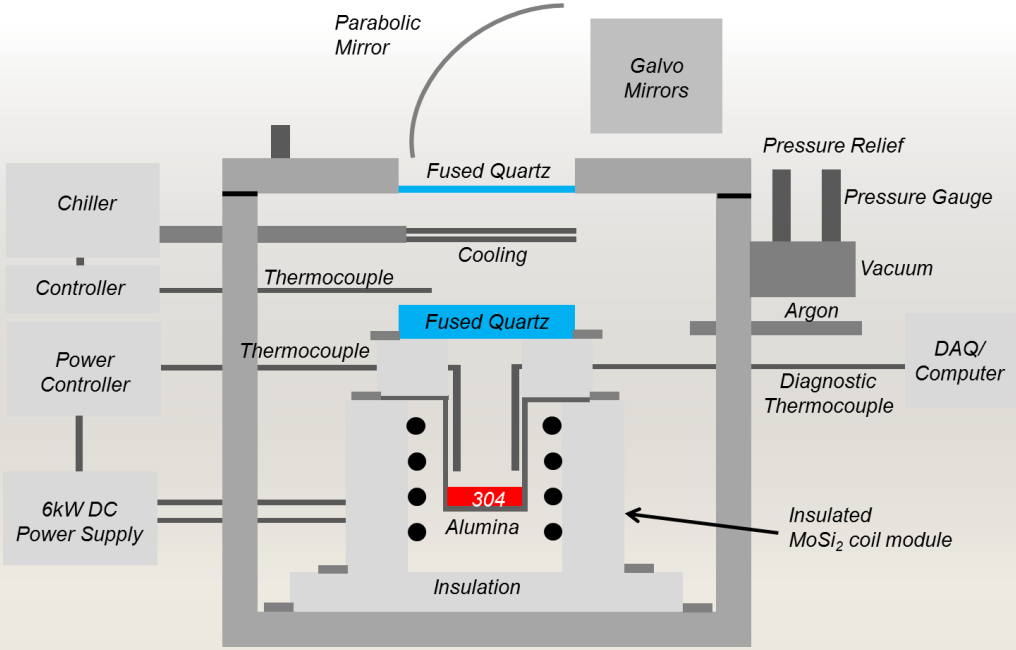
Kinetic Monte-Carlo process models using SPPARKS
(http://spparks.sandia.gov)

Model of a Powder-Bed AM Process to use in mechanical modeling to understand effect of AM processing history on material and structural performance.

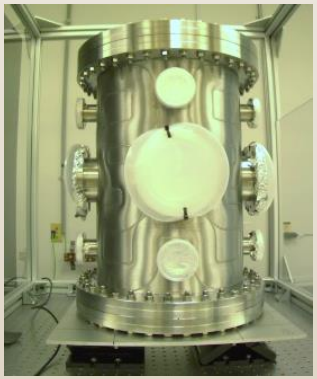
Joe Bishop, Mario Martinez, Theron Rodgers, Jon Madison

Calibration Testbed for IR Sensors

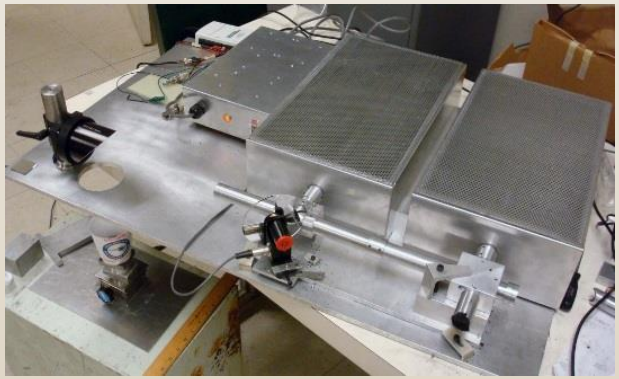
- Using microwave radiometers to measure emissivity & temperature
  - measures %R of 137 GHz radiation from surface
  - 20-1500°C, 2 Torr in Ar chamber
  - expected uncertainty ~10°C
- MIT collaboration



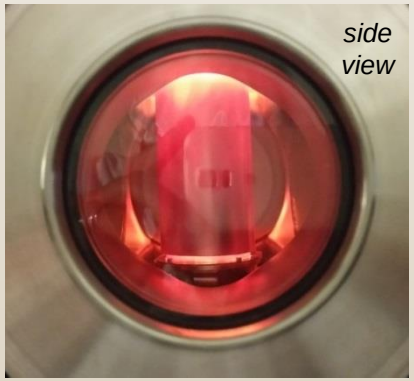
metrology testbed layout

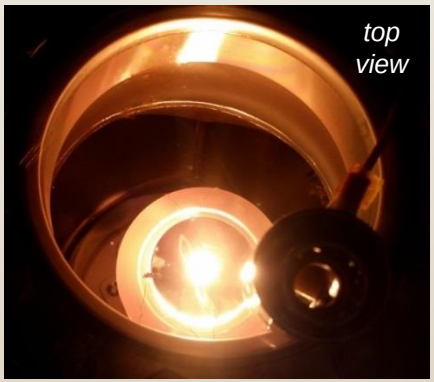


vacuum chamber



137 GHz radiometers

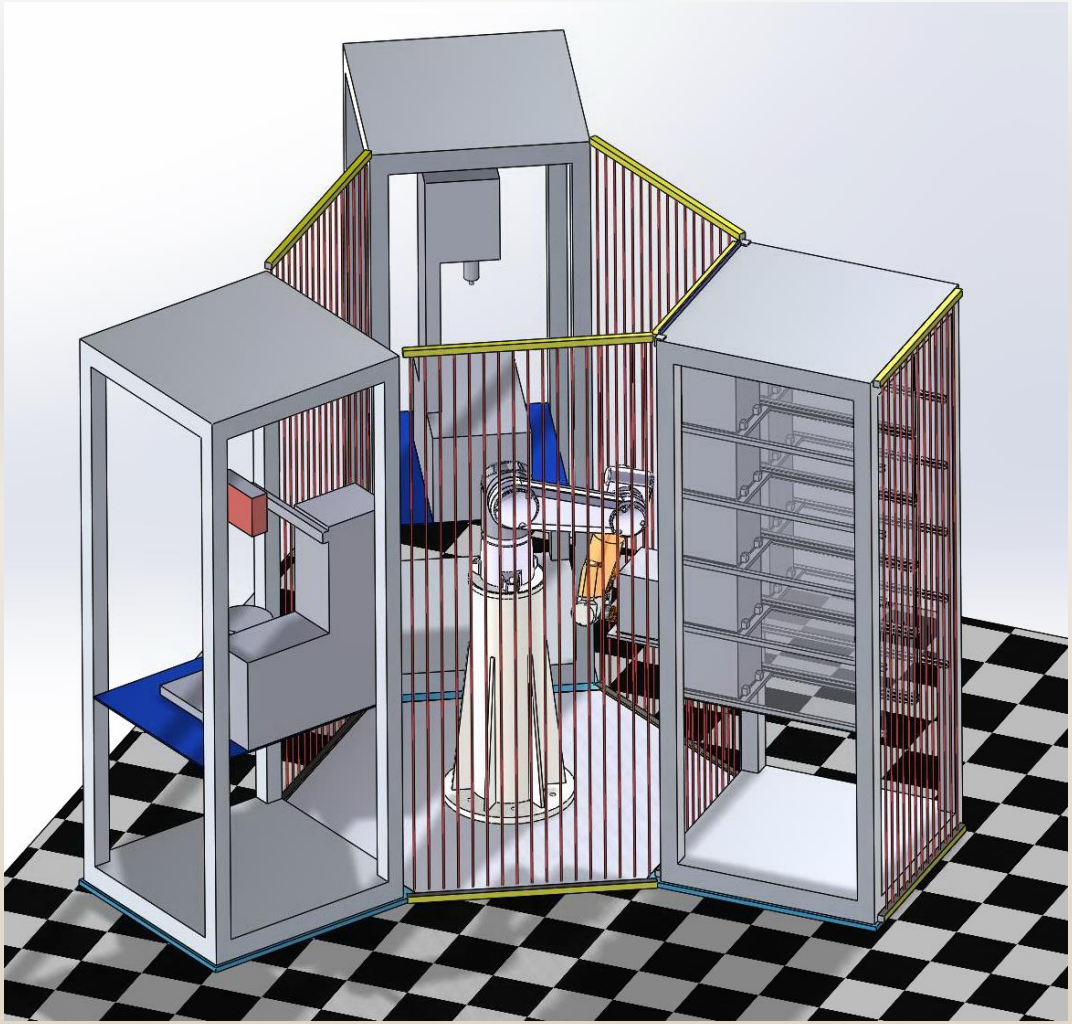




1500 °C furnace in operation

Eric Forrest, Ryan Murphy, Hy Tran

Alinstante Characterization Cell

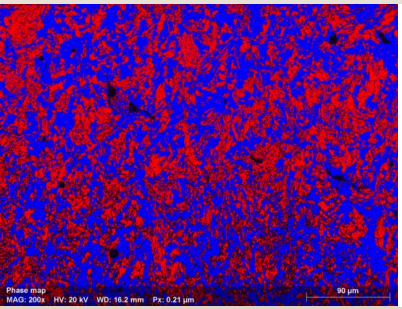


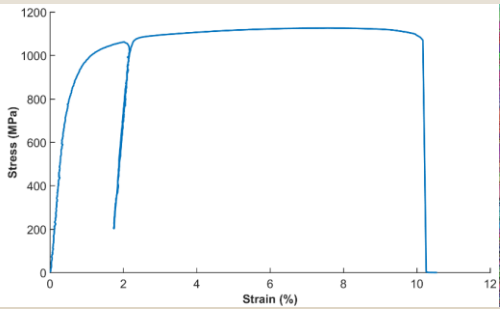
QUESTIONS?

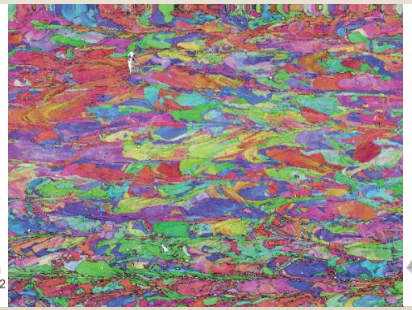
Bradley Jared, PhD

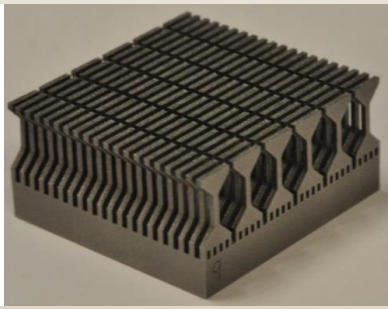
bhjared@sandia.gov

505-284-5890

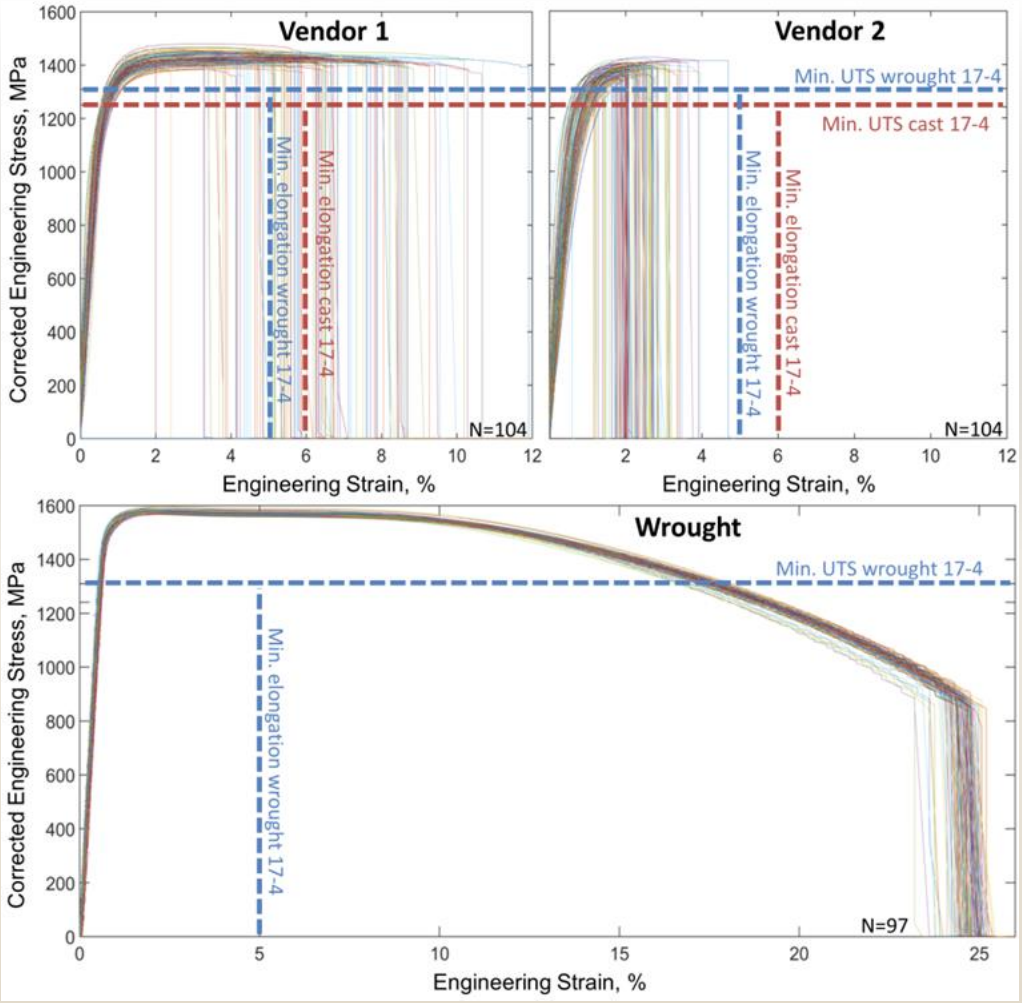




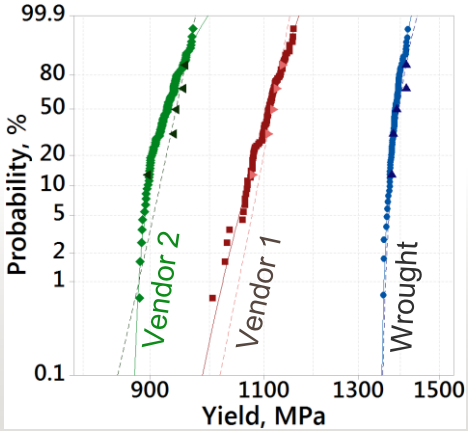


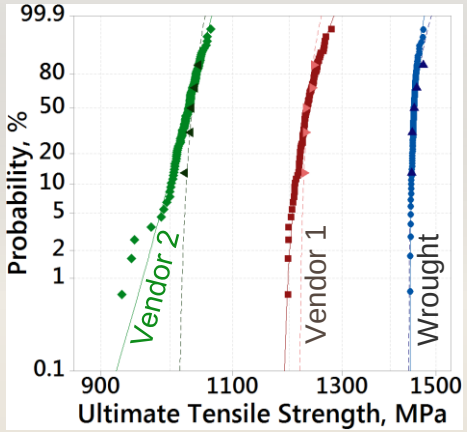


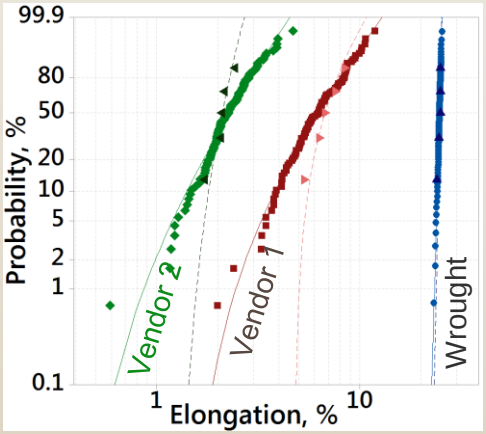
AM vs. Wrought 17-4PH



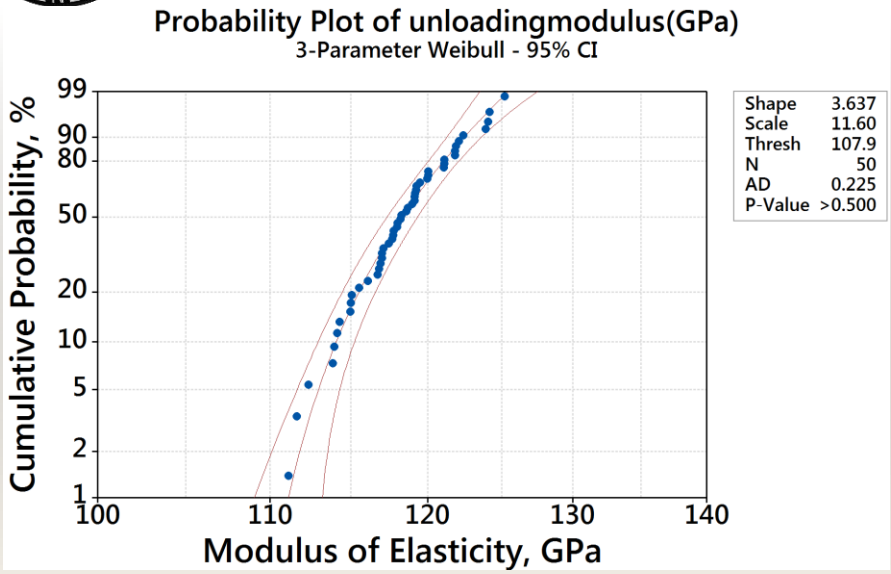
H900 data for vendor 1 (top left), vendor 2 (top right) & wrought (bottom) w/corrected stress area

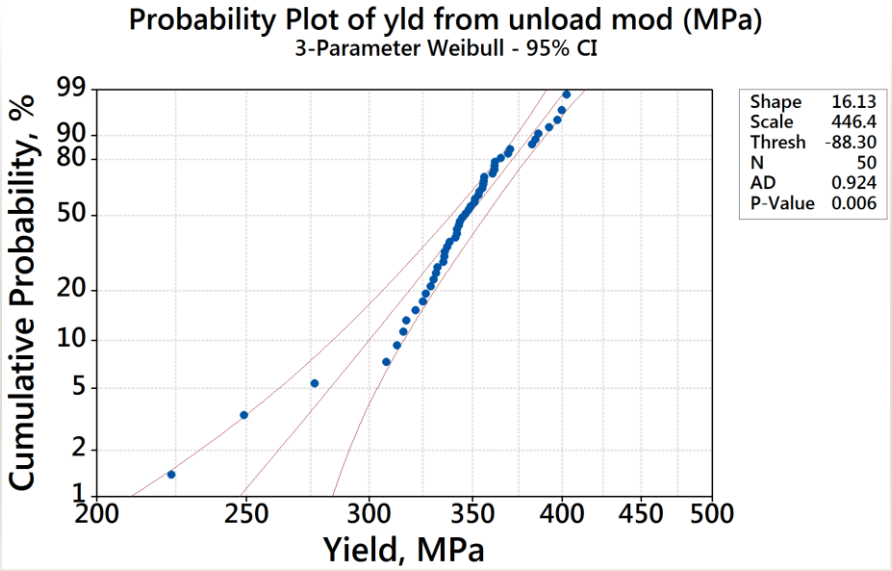


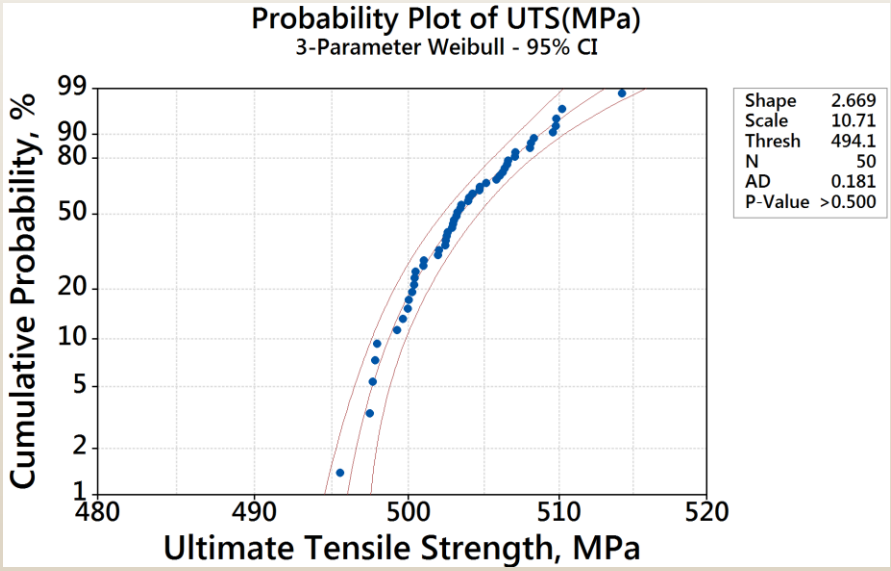


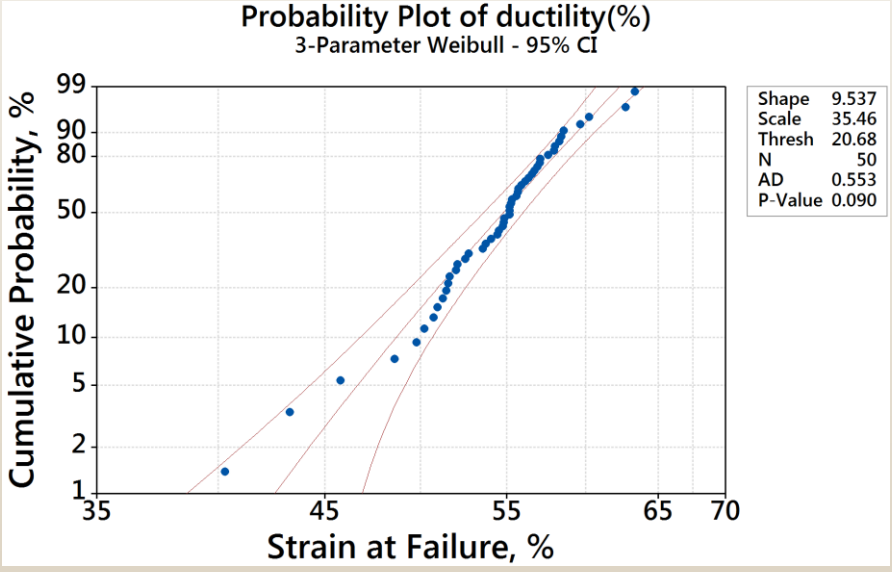


316L Property Distributions



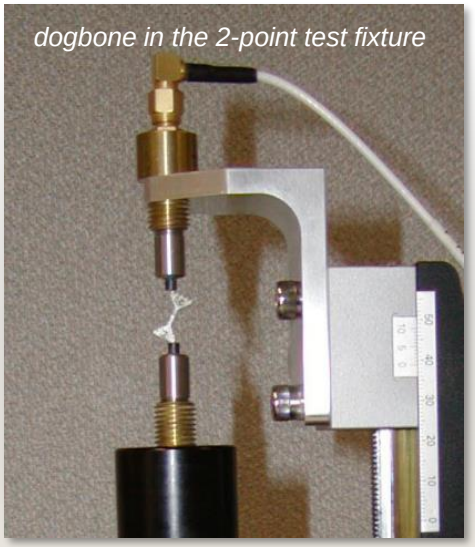


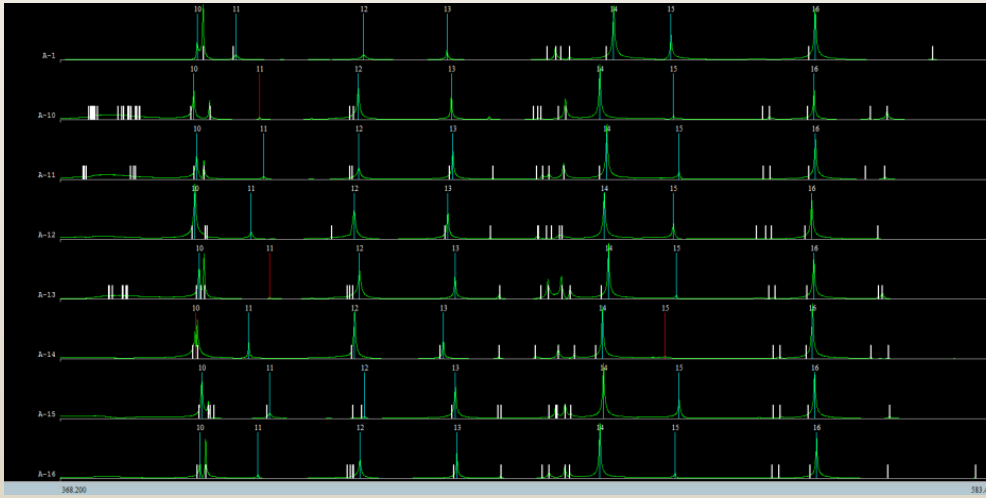




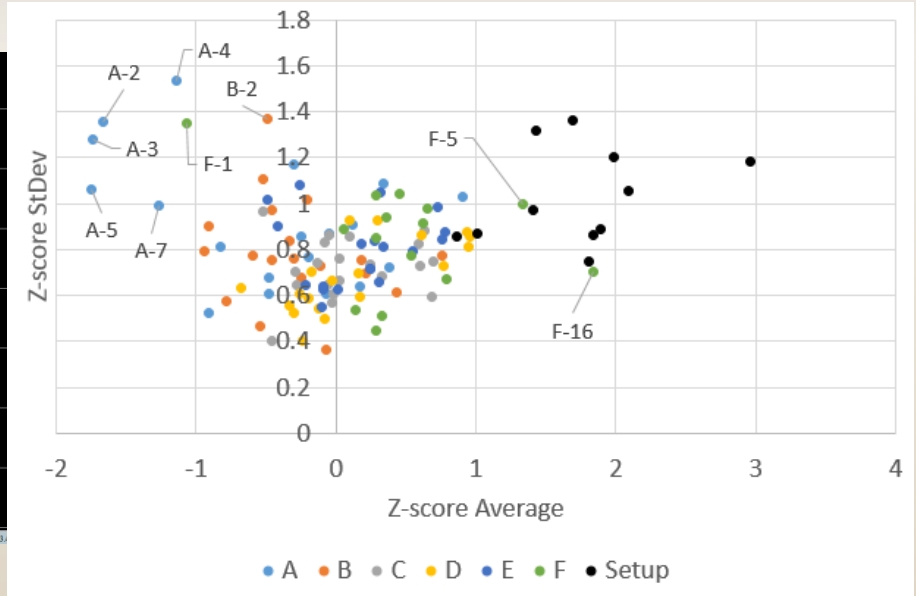
Resonant Ultrasound Spectroscopy

- Swept sine wave input from 2-point transducer
  - 74.2 kHz to 1.6 MHz input spectrum
  - 28 sub-bands record 19 resonances
- Identify resonance peaks
  - Z-score compares peak frequency w/average & std. dev.
  - identify outliers, variations, process limits, defects





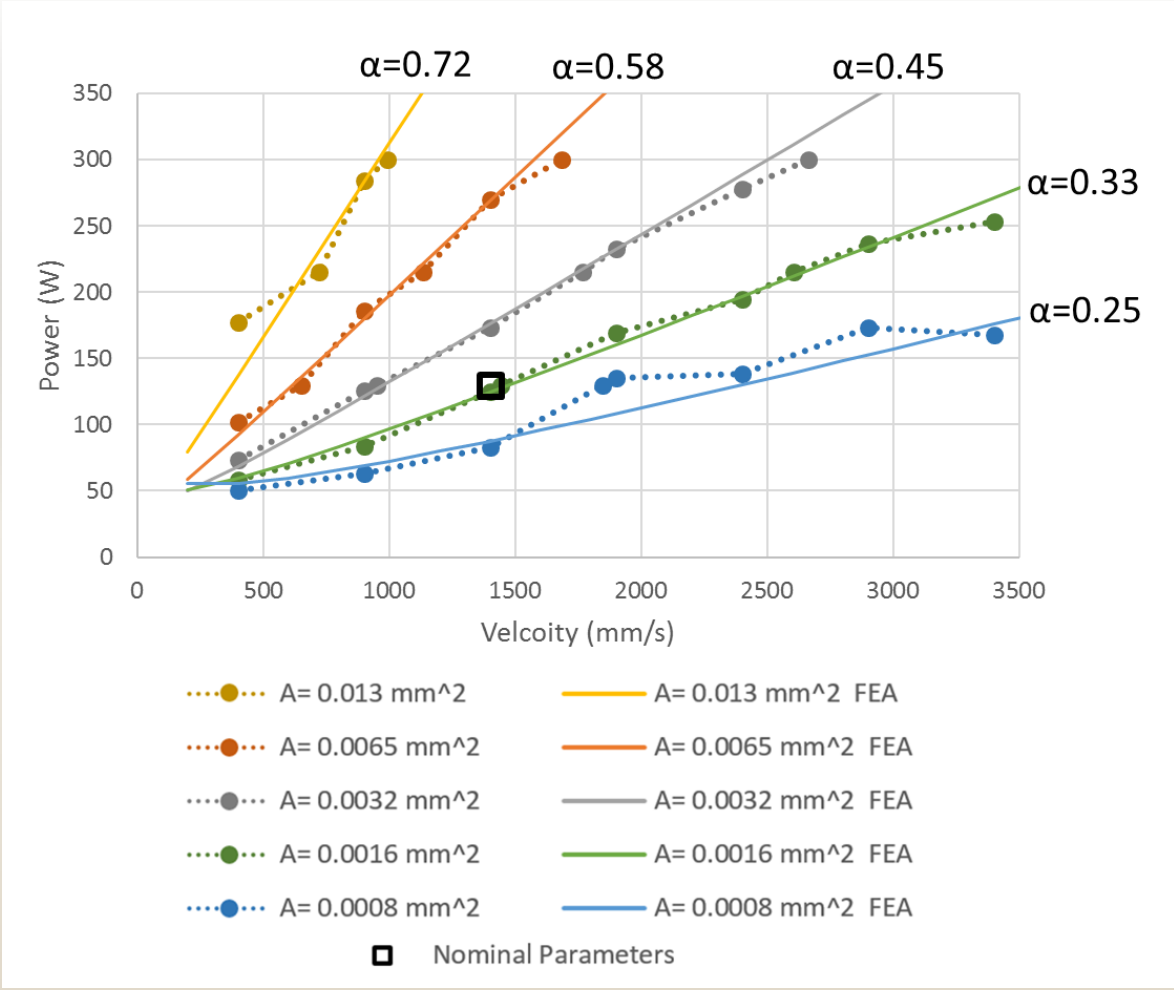
resonance response spectra



dogbone Z-score data spread

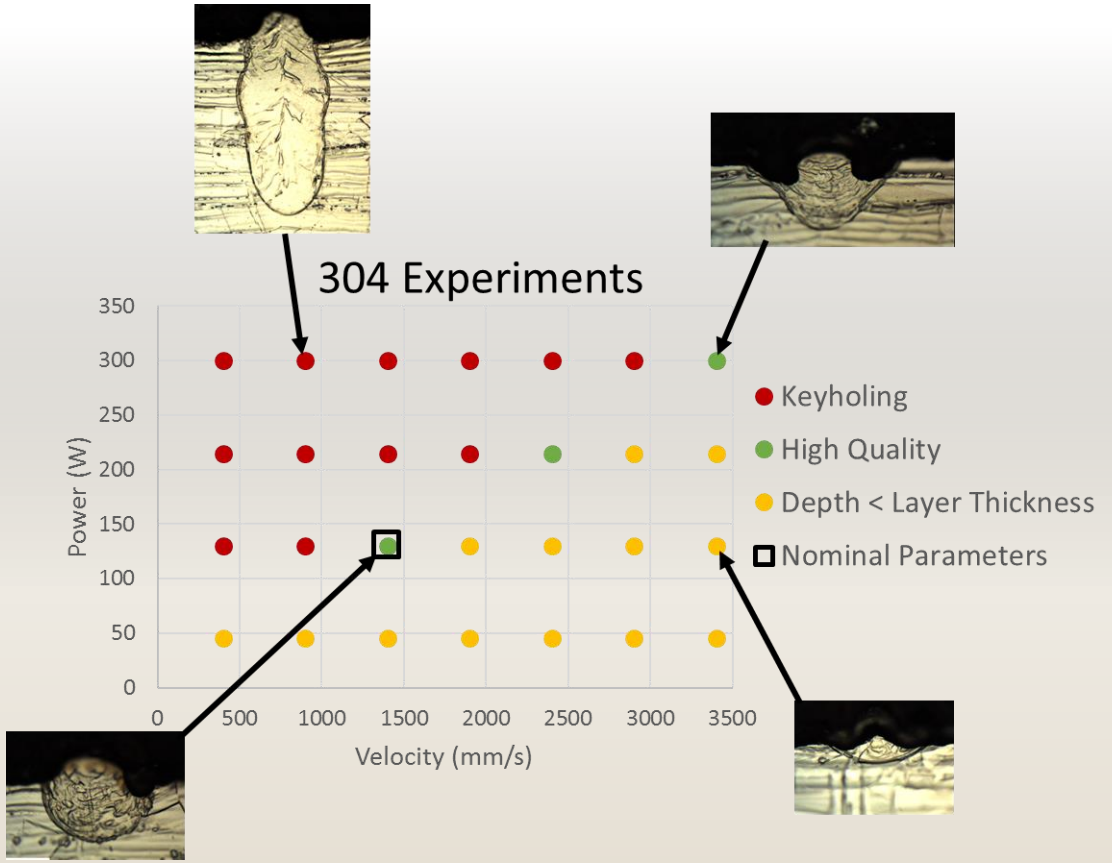
CMU P-V Process Mapping

- 304L process map for single bead experiment
  - lines represent constant cross-section in P-V space
- FEA analysis fit to data by varying effective absorptivity (α)



CMU Process Data

- Melt pool width, depth, and area measured from each deposit
- Width and depth were compared to identify points which were susceptible to keyholing **(red)**
- Points with depth <30µm would be very prone to undermelting porosity **(yellow)**
- **Only 3 of the 28 points are considered high quality (nominal being one of them)**
- Defocus of beam provides higher quality melt pools
  - follow-on testing will explore operation at defocus



defocus results